A Flow Measurement Guide
for Industry Bioengineers

MECHANICAL CIRCULATORY SUPPORT

transonic
THE MEASURE OF BETTER RESULTS.

www.transonic.com

Transonic Applications

Transonic began partnering with outside companies shortly after its inception in 1983 to develop innovative devices. Soon, a robust Transonic/Customer synergy developed between Transonic and device manufacturers and this vital Customer/Manufacturer relationship has become part of Transonic's DNA. It lies at the heart of the development of all Transonic products.

Our applications range from utilizing standard products straight off the shelf to creating such novel designs that they would not be recognized as a Transonic product. Together with our collaborators, Transonic has striven to push the limit on flow measurements including ultra-low flow applications in novel measurement mediums. Transonic customized Flowsensors and Flowboards are being used in a wide range of products and applications including:

Mechanical Circulatory Support Devices including:

1. Heart Lung Machines
2. Extracorporeal Membrane Oxygenation (ECMO) circuits
3. Artificial Hearts (AH)
4. Ventricular Assist Devices (VADs)

Renal Replacement Devices: Hemodialysis Machines

Organ Preservation Devices

Treatment Delivery /Therapy Devices

1. Anesthesia Delivery / Pain Management Systems including:
2. Organ Infusion Pumps
3. Urodynamic System / Urometer
4. Pediatric Hydrocephalus
5. Endometrial Ablation
6. Ocular Surgery

Many More Possibilities

A sampling of the broad spectrum of Transonic application will be presented along with the solutions that Transonic offers for each application.

Measuring Pump Flow with Tubing Sensors

The fist-sized human heart is an incredibly precise pump. To be exact it is two pumps separated by a wall down the middle and encased in a single sheath of muscle. Each side has two chambers, a receiving tank atrium and a ventricle pump. The right side sends blood gently to the lungs, while the left side pump propels five quarts of oxygen-rich blood per minute throughout the body. The heart beats 2.5 billion times in a 70-year-old person's life.

Although the two pumps within the heart must exert significantly different forces, their synchronous beat ensures that blood flow is smooth and continuous. When blood flow no longer is smooth and continuous, heart failure ensues and the heart's action must be augmented. Mechanical circulatory support is one therapy used to help a failing heart pump.

The need for mechanical circulatory support for heart failure is daunting. There are an estimated 5.7 million Americans with heart failure. That number is expected to increase to over eight million by 2030.[1] Of these, nearly one million have end-stage heart failure and are no longer responsive to maximal medical therapy.

The ultimate and ideal goal for these patients is to receive a heart transplant, but in actuality only 2-4% will receive a new heart. Many will die waiting for a transplant. In the interim, many of these patients depend on a variety of mechanical circulatory support devices to improve their cardiac outflow, hemodynamics, and tissue perfusion.

A host of mechanical circulatory support devices are now available. Temporary devices include the intraarotic balloon pump and the bypass pump, both used during cardiothoracic surgery, ECMO systems for more extended heart and/or pulmonary bypass, and percutaneous ventricular assist devices (pVADs). Longer term solutions for heart failure include implantable VADs and total artificial hearts.

All these devices attempt to augment, replace or restore the function of the body's most essential pump, the heart. They pump flow. Therefore, their flows must be accurate and verified. Tubing flow measurements with Transonic's highly accurate Tubing Sensors fill this need.

This section will address four mechanical circulatory support devices and modalities: the heart bypass pump, extracorporeal membrane oxygenation (ECMO), temporary and permanent ventricular assist devices (VADs) and the artificial heart.

Reference

[1]Ergle K *et al*, Ochsner J 2016; 16: 243-249.

Mechanical Circulatory Support

A Cardiopulmonary Bypass (CPB) pump, often referred to as a heart lung machine or simply as "the pump," mimics the function of the heart and lungs by temporarily taking over the heart's and lung's function during surgery. This enables the surgeon to operate in a bloodless surgical field.

The CPB pump was first used by Dr. John H. Gibbon, its developer, in 1953 during successful open heart surgery. Now used during coronary artery bypass (CABG) and other cardiothoracic surgeries as well as heart and lung transplantation, the heart-lung machine has become a fixture in any modern cardiac surgery operating room.

Transonic Solution
Volume Flow Measurement

Clamp-on Tubing Flowsensors connect to a Transonic® Flowmeter to provide an independent measure of actual flow. The system provides noninvasive, sterile measurements without any contact with the liquid or interruption of tubing. It has a stable and low zero offset and calibration can be adjusted on site. The Transonic Tubing Flowsensor/Flowmeter system is the "Gold Standard" used throughout the biomedical and surgical community in order to calibrate & validate heart/lung pumps.

System Benefits
- Maintains tubing integrity;
- Sensor clips onto existing tubing;
- Exhibits unmatched accuracy ± 10%

Measurement Benefits
- Optimizes flow;
- Provides early waring signs of distress, reducing adverse events and improving clinical outcomes.

Transonic Solution
Bubble Detection

TTFM detects bubbles that are 20% or larger than the inner diameter of the tubing. Bubble detection algorothms can be integrated into your device to stop the pump when bubbles are detected or to send a message to the user.

ECMO & Critical Care

2018

Krivitski N et al, "In vitro and in vivo assessment of oxygenator blood volume for the prediction of clot formation in an ECMO circuit (theory and validation)," Perfusion 2018; 33(IS): 51-56. (Transonic Reference # ELS11317)

2016

Palmér O *et al, "Cannula Design and Recirculation During Venovenous Extracorporeal Membrane Oxygenation,"* ASAIO J. 2016; 62(6): 737-742. (Transonic Reference # EC11034AH)

2015

Said MM *et al, "**Precision & Accuracy of the New Transonic ELSA Monitor to Quantify Oxygenator Blood Volume (in-vivo and in-vitro studies),"*** 2015 PAS Annual Meeting and Eastern SPR Annual Meeting. (Transonic Reference # ELS10230V)

2012

Körver EP **et al, *"Quantification of recirculation as an adjuvant to transthoracic echocardiography for optimization of dual-lumen extracorporeal life support,"*** Intensive Care Med. 2012 38(5): 906-909. (Transonic Reference # ELS9679AH)

2009

*Walker JL, Darling E **et al, "Calculating mixed venous saturation during veno-venous extracorporeal membrane oxygenation,"** Perfusion. 2009; 24(5): 333-9. (Transonic Reference # 7904A)*

2006

Darling EM, Crowell T, Searles BE, ***"Use of dilutional ultrasound monitoring to detect changes in recirculation during venovenous extracorporeal membrane oxygenation in swine,"*** ASAIO J 2006; 52(5): 522-4. (Transonic Reference # 7309A)

2006

Van Heijst AF ***et al, "Recirculation in double lumen catheter veno-venous extracorporeal membrane oxygenation measured by an ultrasound dilution technique,"*** ASAIO J, 2001; 47(4): 372-6. (Transonic Reference # HD49V)

1997

Snyder EJ ***et al, "Setting roller pump occlusion with the Transonic HT109 Flowmeter,"*** ASAIO J 1997; 43: 60-64. (Transonic Reference # 517AH).

1996

Berube MC ***et al, "Ultrafiltration in the Cardiac ECMO Patient: Use of the Transonic HT109 Flowmeter to Determine Hemofilter Shunt and Actual Flow,"*** 12th Annual CNMC Symposium on ECMO & Advanced Therapies for Respiratory Failure, Keystone, CO, Feb 25-29, 1996. (Transonic Reference # 715A)

1990

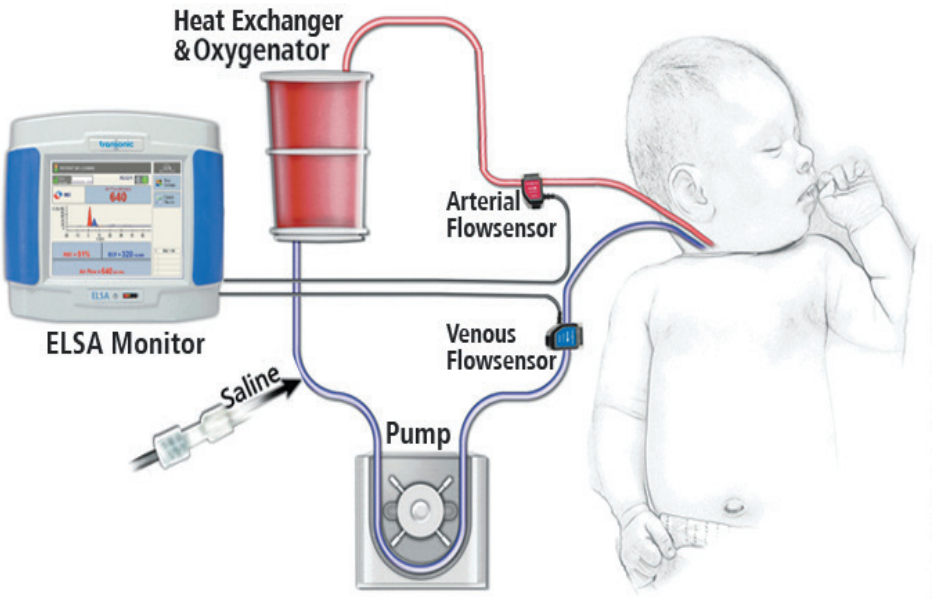
Akers T *et al,* **"In Vitro Comparison (electromagnetic, Doppler, pump occlusion & transit-time) of ECC Blood Flow Measurement Techniques,"** Proceedings of the ASET, 1990; 17-22. (Transonic Reference # 28V)

1987-89

Vilard J, Powers RJ, ***"Relationship of Temperature and Hematocrit to the Accuracy of Flow Measurement by Transit Time Ultrasound,"*** ELSO Extracorporeal Life Support Organization, 1989; 1: 23. (Transonic Ref# 16V) Dr. Robert Bartlett write Flowsensor into ECMO protocol to measure pump flow. C-Series Clamp-on sensors introduced or noninvasive sterile tubing use; adopted by ASAIO for TAH, VADs, CPB and ECMO

ECMO: Temporary Mechanical Circulatory Support

"Use of the Transonic Flowmeter allows the ECMO specialist to monitor actual patient blood flow and hemofilter shunt enhancing patient care management" *Berube, MC*



Schematic of ELSA System with touch screen computer/monitor and Flowsensors clipped onto the tubing lines on either side of the oxygenator.

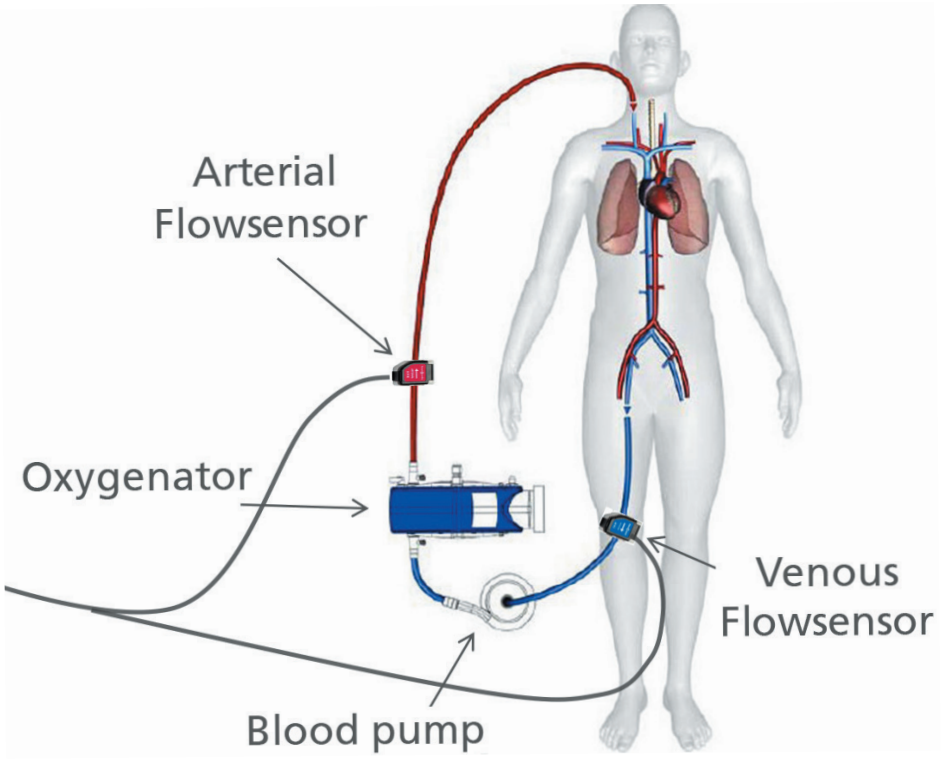
Extracorporeal membrane oxygenation (ECMO) is the use of prolonged extracorporeal cardiopulmonary bypass (CPB) in patients with acute, reversible cardiac or respiratory failure. Although ECMO is the most common term to describe this procedure, extracorporeal life support (ECLS) and cardiopulmonary life support (CPS) are also commonly used. The two most common types of ECMO are veno-arterial (VA) and veno-venous (VV) ECMO. In both, blood drained from the venous system is oxygenated outside of the body by an oxygenator. In VA ECMO, this blood is returned to the arterial system providing circulatory support. In VV ECMO the blood is returned to the right heart and no cardiac support is provided.

The use of ECMO in adults increased during the 2009/2010 H1N1 influenza pandemic. Within a day of the flu's onset, a small percentage of adults were struck with rapid, progressive Adult Respiratory Disease Syndrome (ARDS). This increased exposure and highlighted its importance.

ECMO: Temporary Mechanical Circulatory Support

Adult ECMO

ELSA Monitor



Schematic of ELSAystem connected to an adult patient showing placement of arterial and venous sensors, and cannulas in the femoral artery and vena cava.

New ECMO centers are continuing to be established to serve as a last resort therapy for such life threatening complications. The Extracorproeal Life Support Organization (ELSO) provided guidelines for use of ECMO in adults with cardiac failure that include:

- Inadequate tissue perfusion (hypotension and low cardiac output;
- Shock persisting despite volume adminis-tration, inotropes and vasoconstrictors, and intra-aotic balloon counter-pulsation, if appropriate;
- Typical causes: acute myocardial infarction, myocarditis, peripartum cardiomyopathy, decompesated chronic heart failure, post-cardiotomy shock;
- Septic shock (indication in some centers).

ECMO: Temporary Mechanical Circulatory Support

The ELSA Monitor

Transonic's Extracorporeal Life Support Assurance (ELSA) Monitor is a new state-of-the-art biomedical instrument that is used to optimize and safeguard extracorporeal membrane oxygenation (ECMO) therapy in infants, children and adults. It uses two gold standard technologies (transit-time ultrasound & ultrasound flow/dilution) to provide the following:

HC101 ELSA Monitor

The ELSA Measures:

- Delivered (pump) flow in the ECMO circuit
- Recirculation
- Oxygenator Blood Volume

Delivered Blood Flow by TTFM

A clamp-on sensor transmits beams of ultrasound through the blood line many times per second. Two transducers pass ultrasonic signals back and forth, alternately intersecting the flowing blood in upstream and downstream directions. The ELSA derives an accurate measure of the changes in the transit time it takes for the wave of ultrasound to travel from one transducer to the other resulting from the blood flow in the vessel. The difference between the upstream and downstream transit times and the area of the tubing provide a measure of volume flow.

During ECMO, two matched flow/dilution sensors are clipped onto the arterial and venous lines. The monitor continuously displays both blood flows. Comparison of the readings with the pump flow setting (i.e., the flow the pump is assumed to deliver) provides an opportunity to identify and correct flow delivery problems.

Patient Blood Flows, Recirculation, Oxygenator Blood Volume by UDT

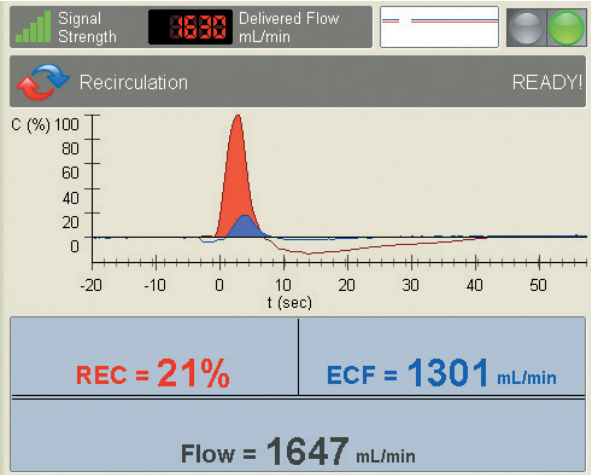
The velocity of ultrasound in blood (1560-1590 m/sec) is determined primarily by its blood protein concentration. The ELSA Monitor and its matched Flow/dilution Sensors measure ultrasound velocity. A bolus of isotonic saline (ultrasound velocity: 1533 m/sec) introduced into the blood stream dilutes the blood and reduces the ultrasound velocity. The Sensor records this saline bolus as a conventional indicator dilution curve. When a bolus of saline indicator is introduced into the blood line, the arterial and venous sensors each register an indicator dilution curve.

ECMO: Temporary Mechanical Circulatory Support

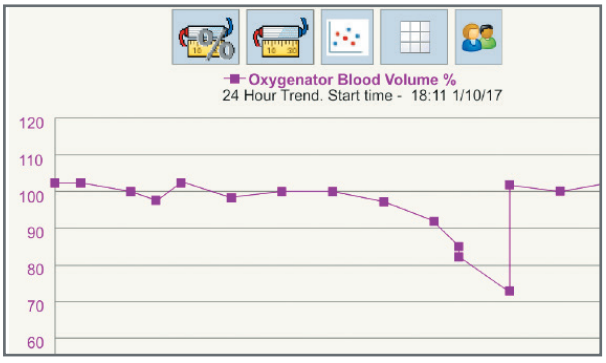
Recirculation

When a saline bolus is injected upstream from the arterial Flowsensor, the ELSA identifies the saline concentrations at both Flowsensors. The ratio of indicator concentrations equals recirculation.

Rec= Sv/Sa*100%; where Sa and Sv are areas under the respective arterial and venous dilution curves.



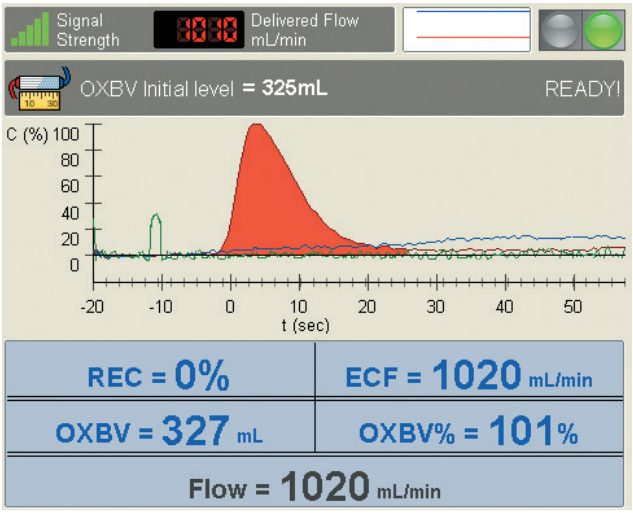
Recirculation Results (21%) screen during VV ECMO. Also shown are the effective cardiac flow and the pump flow.



Oxygenator Blood Volume trended as a percentage.

Oxygenator Blood Volume

When a saline bolus is injected upstream from the oxygenator, the time that the indicator takes to travel through the oxygenator is proportional to its blood volume. OXBV = Qb * MTT; where Qb is blood flow through oxygenator and MTT is mean transit time of indicator travel through oxygenator. Percent change of OXBV% in time can be expressed: OXBV% = OXBVt / OXBVi*100%; where OXBVt is the value of OXBV measured at any moment in the ECMO process. OXBVi – initial OXBV measured at the beginning of ECMO process when oxygenator is free of clots. A decrease in oxygenator blood volume over time reflects poor oxygenator performance clotting onset clotting within the circuit.



ELSA results screen shows oxygenator blood volume (OXBV) (327 mL). Oxygenator blood volume percentage (101%) plus delivered blood flow (1020 mL/min), effective flow (1020ml/min) and recirculation (0%) during VV ECMO.

ECMO: Temporary Mechanical Circulatory Support

Krivitski N, Galyanov G, Cooper D, Said MM, Rivera O, Mikesell GT, Rais-Bahrami K, **"*In vitro* and *in vivo* assessment of oxygenator blood volume for the prediction of clot formation in an ECMO circuit (theory and validation),"** Perfusion 2018; 33(IS): 51-56. (Transonic Reference # ELS11317)"Dilution technology has the ability to accurately and reproducibly assess the clotting process in the oxygenator."

Ruß M, Weber-Carstens S, Skrypnikov V, Taher M, Francis RCE, BoemkeW, Pickerodt PA, **"Optimization of V-V ECMO circuit determined by blood recirculation measurements improved systemic oxygenation in a 10-year-old patient,"** 5th Annual Symposium on ARDS, Berlin, Germany, June 2019 (Transonic Reference: ELS10569A) When initiation of high flow V-V ECMO did not sufficiently support systemic oxygenation in the child, measurements of recirculation, imaging techniques and applied ECMO physiology did lead to optimization of systemic oxygenation and lung protective ventilation.

Said MM, Mikesell GT, Rivera O, Khodayar Rais-Bahrami K, **"Precision and Accuracy of the New Transonic ELSA Monitor to Quantify Oxygenator Blood Volume (*in-vivo* and *in-vitro* studies),"** 2015 PAS Annual Meeting and Eastern SPR Annual Meeting. (Transonic Reference # ELS10230V) The ELSA monitor would be a valuable tool to identify early clot formation in ECMO circuits and allow device change outs before they become a clinically emergent.

Said MM, Mikesell GT, Rivera O, Khodayar Rais-Bahrami K, **"Influence of central hemodynamics and dual-lumen catheter positioning on recirculation in neonatal veno-venous ECMO,"** 2015 PAS Annual Meeting and Eastern SPR Annual Meeting. (Transonic Reference # ELS10231V) "Using the injection of a small volume of saline, the ELSA monitor provides a non-invasive method to measure recirculation and optimize catheter performance in an ECMO circuit."

Palmér O, Palmér K, Hultman J, Broman M, **"Cannula Design and Recirculation During Venovenous Extracorporeal Membrane Oxygenation,"** ASAIO J. 2016; 62(6): 737-742. (Transonic Reference # EC11034AH) "By utilizing the ultrasound dilution technique to measure Rf before and after repositioning, effective ECMO flow can be improved for a more effective ECMO treatment."

Körver EP, Ganushchak YM, Simons AP, Donker DW, Maessen JG, Weerwind PW, **"Quantification of recirculation as an adjuvant to transthoracic echocardiography for optimization of dual-lumen extracorporeal life support,"** Intensive Care Med. 2012 38(5): 906-909. (Transonic Reference # ELS9679AH) "We present an ultrasound dilution technique allowing quantification of recirculation for optimizing vv-ELS. ...Conclusion: We suggest quantification of recirculation in addition to image guidance to provide optimal vv-ELS."

Clements D, Primmer J, Ryman P, Marr B, Searles B, Darling E, **"Measurements of recirculation during neonatal veno-venous extracorporeal membrane oxygenation: clinical application of the ultrasound dilution technique,"** J Extra Corpor Technol. 2008;40(3):184-7. (Transonic Reference: ELS9680AH) "In this initial case experience, ultrasound dilution technique provided quick, reproducible beside results that showed changes in recirculation associated with VV ECMO therapy...This paper shows that ultrasound dilution technology can be used to quantify recirculation in neonates on VV ECMO."

Walker JL, Gelfond J, Zarzabal LA, Darling E, **"Calculating mixed venous saturation during veno-venous extracorporeal membrane oxygenation,"** Perfusion. 2009; 24(5): 333-9. (Transonic Reference # 7904A) Recirculation (R), the shunting of arterial blood back into to the venous lumen, commonly occurs during veno-venous extracorporeal membrane oxygenation (VV-ECMO) and renders the monitoring of the venous line oxygen saturation no longer reflective of patient mixed venous oxygen saturation (S(V)O(2))

Melchior R, Darling E, Terry B, Gunst G, Searles B, **"A novel method of measuring cardiac output in infants following extracorporeal procedures: preliminary validation in a swine model,"** Perfusion 2005; 20(6): 323-7. (Transonic Reference # 10234A) This pilot study demonstrated that the CO UD technique correlates to other benchmarks of CO measurements.

Darling EM, Crowell T, Searles BE, **"Use of dilutional ultrasound monitoring to detect changes in recirculation during venovenous extracorporeal membrane oxygenation in swine,"** ASAIO J 2006; 52(5): 522-4. (Transonic Reference # 7309A) "Dilutional ultrasound provides a clinically practical method to quantify and monitor recirculation in VV ECMO applications and may aid in assessing interventions to improve oxygen delivery."

van Heijst AF, van der Staak FH, de Haan AF, Liem KD, Festen C, Geven WB, van de Bor M, **"Recirculation in double lumen catheter veno-venous extracorporeal membrane oxygenation measured by an ultrasound dilution technique,"** ASAIO J, 2001; 47(4): 372-6. (Transonic Reference # HD49V) "The ultrasound dilution method is a useful method for measurement of the recirculation fraction in DLVV-ECMO and is easier to use than the other methods."

Permanent Mechanical Circulatory Support

The 1980s was a milestone decade in the development of artificial hearts assist devices for permanent use in cardiac failure patients. In 1982, retired dentist Barney Clark received an artificial heart at the University of Utah and survived for 112 days. By 1985, five more implantations of the Jarvik 7 artificial heart had been performed. William Schroeder was the longest survivor, living for 620 days with the Javik 7 heart. By the end of the decade, surgeons at 16 centers had used the Jarvik 7 as a bridge to heart transplantation in more than 70 patients. In 1988, Jarvik Heart, Inc. and the Texas Heart Institute began developing the second generation Jarvik 2000 Heart.

Javik 2000 Total Artificial Heart

From the outset, cardiac pioneers such as Dr. Michael DeBakey recognized the need to measure and verify flow in these innovative artificial heart devices and incorporated Transonic flow measurement in the first MicroMed artificial hearts developed with NASA. The current version ReliantHeart5 still boasts this competitive advantage of offering True Flow.

Cardiovascular Explorer George Pantalos

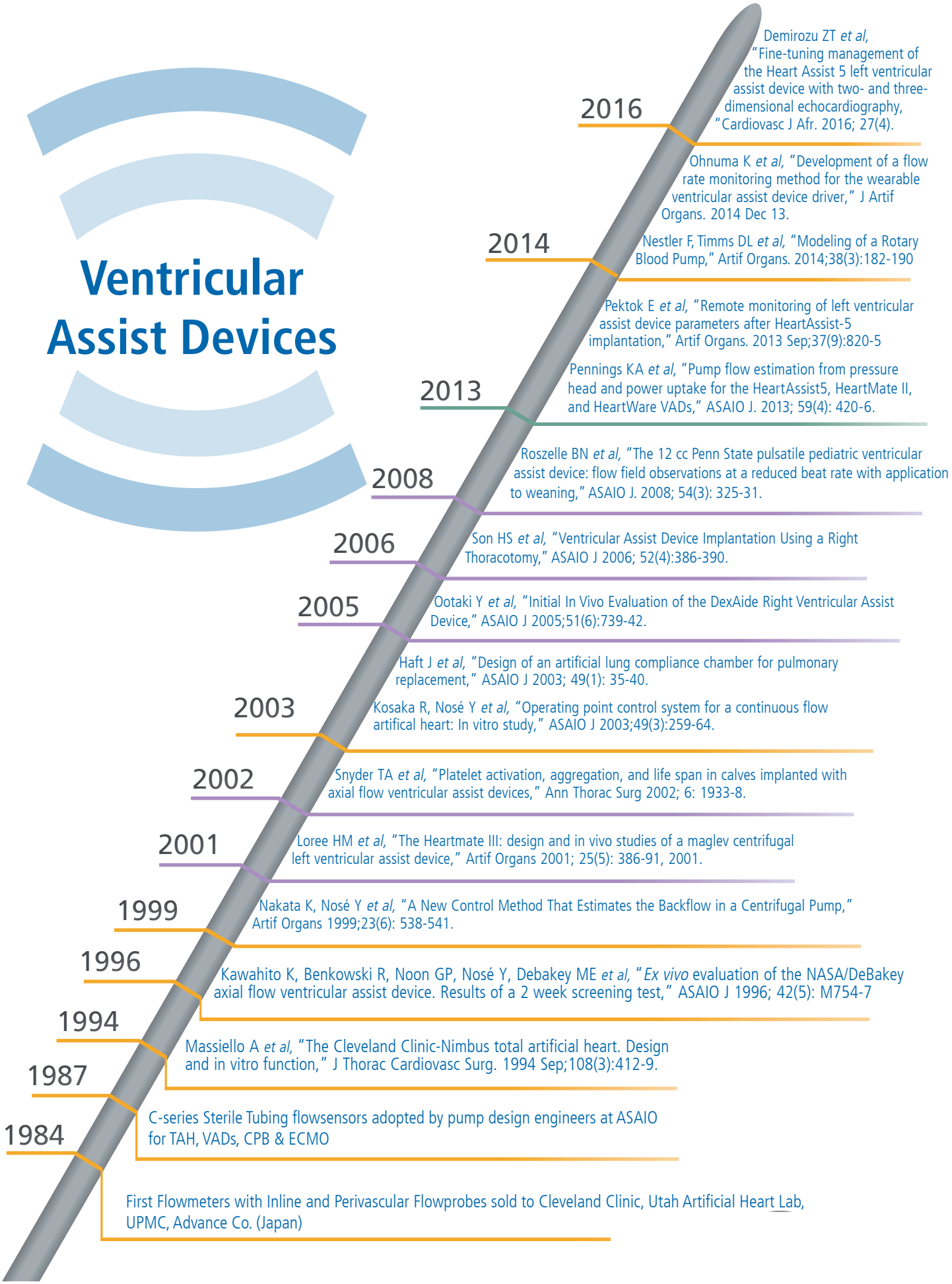
The painstaking development of artificial hearts to replace failed human hearts coincides with development of robust mock circulatory systems that mimic human circulation. Transonic's longtime collaborator and cardiovascular explorer George M. Pantalos, Ph.D. has been instrumental in developing such circulatory systems, first at the University of Utah and now as Professor of Cardiovascular, Thoracic Surgery and Bioengineering at the University of Louisville, KY.

Dr. George Pantalos on one of his 43 research missions on the NASA parabolic flight aircraft working on an instrumented artificial heart beating on a circulation simulator.

Throughout his career, which has included flying 43 research missions on the NASA Zero-G airplane, Dr. Pantalos has tried to understand cardiovascular function by treating heart failure with mechanical devices including artificial hearts and ventricular assist devices which he has helped develop, test and implement clinically in patients.

He and other artificial heart developers have depended on Transonic's highly accurate tubing measurements to verify flow every step along the way in mock tubing circuits, including an artificial heart which has flown twice on the Space Shuttle Discovery.

Ventricular Assist Devices



MECHANICAL CIRCULATORY SUPPORT

Transonic history is providentially intertwined with the development of circulatory support and Ventricular Assist Devices (VADs). In 1971, Transonic President Cor Drost was recruited by Dr. Yukihiko Nosé at the Cleveland Clinic to work on projects that included development of centrifugal and axial blood pumps for cardiac assist.

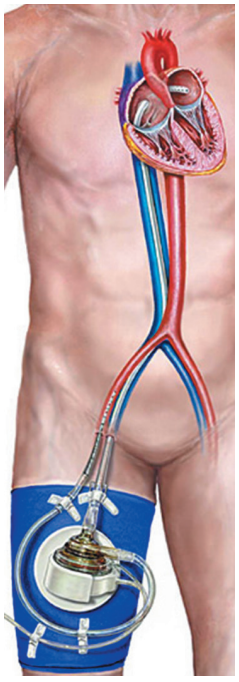
Grant funding fell through and Cor came to Cornell University to work with Professor Alan Dobson to design a more reliable Doppler flowmeter to measure blood flow in conscious animals. His invention was a transit-time volume flowmeter that has been used in the engineering and testing of almost every circulatory support device in the last quarter century.

The first tubing flowsensors developed in 1987 could readily measure volume flow of water, saline and blood analogs like glycerin & water solutions used to mimic the viscosity of blood and best assess pump design on the bench. For extracorporeal devices, clamp-on tubing flowsensors had no contact with the liquid and would keep blood lines sterile. And ultimately, the flowsensors would be positioned on the artificial vessel outlet graft of the pumps to directly measure pump performance. Examples of such tubing applications follow in this section.

pVAD: Temporary Mechanical Circulatory Support

Cardiogenic shock is characterized by impaired cardiac output leading to reduced systemic perfusion, increased residual volumes in both ventricles and increased cardiac filling pressures. A primary treatment for cardiogenic shock is circulatory support that increases mean arterial pressure and microvascular perfusion, ventricular unloading and myocardial perfusion.

In patients who have developed heart failure as a result of heart surgery or a heart attack, percutaneous ventricular-assist devices (pVADs) are one strategy to achieve this cardiogenic shock treatment goal in the acute setting for a few hours up to 14 days. Because they offer more hemodynamic support than the 40-year-old gold standard of intra-aortic balloon pumps (IABPs), the use of pVADs has increased over the past several years. During the first critical weeks post-op, a pVAD gives a patient's heart time to heal and strengthen, and potentially regain its former function. Percutaneous VADs are also now being used as a bridge to a definitive long-term therapy. pVADs feature a continuous flow pump in an extracorporeal circuit with various deployment configurations customized to support either the left or right heart.

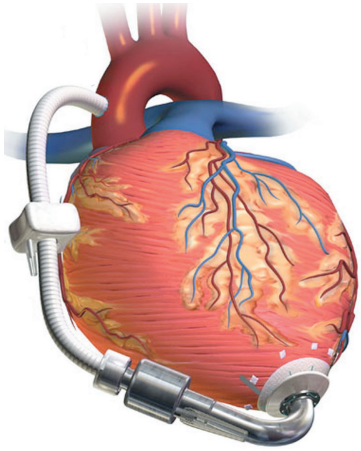


Tandem Heart

To increase mean arterial pressure and microvascular perfusion, some devices use a centrifugal pump to draw blood from the left or right atrium into an extracorporeal circuit. Blood is then returned via the femoral artery. Others uses an axial pump that is inserted retrograde across the aortic valve via the femoral artery.

During each stage in the the development and testing phases of pVADs, simulated flow models that depend on Transonic tubing measurements, tested` the devices.

VAD: Mechanical Circulatory Support



Customized AU Flowprobe on Outflow Cannula of HeartAssist 5 LVAD.

True VAD Outflow

Management of acute right heart failure, a common complication following implantation of a VAD for left ventricular circulatory support, requires a reliable estimation of left ventricular preload and contractility. A Transonic® ultrasonic Flowprobe on a VAD's outflow line provides this information. A progressive decline in outflow accompanied by a loss of pulsatility and other indicators such as lower pressure and/or acute renal failure signals acute right heart failure and earlier measures can be taken to restore flow.

Delivered Blood Flow

Thrombosis is a dreaded complication of having a left ventricular assist device. However, with the unmatched accuracy of Transonic H-XL-Series Clamp-on Tubing Sensors, true blood flow through the circuit can be known at all times. By comparing actual delivered blood flow to the flow reading on the pump, flow limiting causes can be detected and corrected on the spot. Kinks and circuit blockages can be detected and corrected before catastrophic circuit failures with dire consequences can occur.

Transonic's Transit-time Ultrasound flow measurement (TTFM) is a must have for flow verification and confirmation of pump performance. In VADs, where flow equals life, the accurate measurement of volume flow is an essential quality control and safety measure. Transonic's new miniaturized flow chips allow for the direct integration of a four-crystal sensor over the graft tubing of the VAD itself to provide an early alert system for any VAD failures, thrombosis or patient arrhythmias. When integrated into the alert system of the device, the flow measurement can spot trouble before the patient even realizes it and call the patient in for review ahead of adverse events.

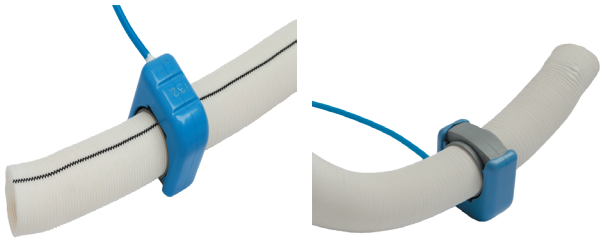
An external clamp-on Flowsensor clips onto the tubing to continuously monitor actual flow delivery to the patient. Measurements are non-invasive, continuous and bi-directional. H-XL Clamp-on Tubing Sensors:

- Measure volume flow in mL or L/min non-invasively;
- Maintain sterility of liquids;
- Offer custom sensor calibration available for different liquids and temperature combinations

VAD: Mechanical Circulatory Support cont.

Surgery to Implant a VAD

Surgery to implant a pVAD or LVAD is precise and precarious. Cannulas must be placed in major arteries, and the heart. Bleeding is a frequent complication, but flow can also be compromised at any moment. Measuring flow intraoperatively with a Transonic Perivascular Flowprobe on the Aorta or Pulmonary artery keeps the surgeon appraised of the function of the heart at all times and allows for early intervention, if necessary.



COnfidence Flowprobes on Dacron grafts.

COnfidence Flowprobes®

COnfidence Perivascular Flowprobes are designed for adult and pediatric, and neonatal intraoperative flow measurements. They can also be customized and calibrated for VAD dacron outflow grafts (see figures). Their small footprint and slim profile permits measurement of volume flow in great arteries and veins with turbulent flow and where a compact Fowprobe is needed. COnfidence Flowprobes:

- Measure volume flow, not velocity;
- Are available in a wide range of sizes including miniature 4 mm and 6 mm sizes for neonatal anatomy;
- Quick, measurements seconds after Flowprobe is applied.

References

Ishino K, **"A hemodynamic study of the biventricular bypass total artificial heart with special reference to intrarenal flow distribution,"** Jpn J Surg. 1991 May;21(3):312-21.

Massiello A, Kiraly R, Butler K, Himley S, Chen JF, McCarthy PM, **"The Cleveland Clinic-Nimbus total artificial heart. Design and in vitro function,"** J Thorac Cardiovasc Surg. 1994; 108(3): 412-9.

Pantalos GM1, Bennett TE, Sharp MK, Woodruff SJ, O'Leary SD, Gillars KJ, Schurfranz T, Everett SD, Lemon M, Schwartz J, **"Effect of Gravitational Acceleration on Ventricular Filling,"** Curr Pharm Biotechnol. 2005; 6(4): 331-41.

Tominaga R, Smith W, Massiello A, Harasaki H, Golding LA, **"Chronic nonpulsatile blood flow. II. Hemodynamic responses to progressive exercise in calves with chronic nonpulsatile biventricular bypass,"** J Thorac Cardiovasc Surg. 1996; 111(4): 857-62.

Tayama E, Olsen DB, Ohashi Y, Benkowski R, Morley D, Noon GP, Nosé Y, Debakey MEm, **"The DeBakey ventricular assist device: current status in 1997,"** Artif Organs. 1999; 23(12): 1113-6.

Noon GP, Morley DL, Irwin S, Abdelsayed SV, Benkowski RJ, Lynch BE, **"Clinical Experience with the MicroMed DeBakey Ventricular Assist Device,"** Ann Thorac Surg. 2001; 71(3 Suppl): S133-8;
(Additional references are on pages 45-47)

Texas Heart Institute St. Luke's Episcopal Hospital, Houston, TX

Nestler F *et al,* "A hybrid mock circulation loop for a total artificial heart," Artif Organs. 2014; 38(9): 775-82. (Transonic Reference # 10038A)

Frazier OH, "Mechanical circulatory assist device development at the Texas Heart Institute: a personal perspective," Semin Thorac Cardiovasc Surg. 2014 ;26(1): 4-13. (Transonic Reference # 10176AHR)

Frazier OH *et al,* "Optimization of axial-pump pressure sensitivity for a continuous-flow total artificial heart," J Heart Lung Transplant 2010; (Transonic Reference # 7920A)

Tuzun E, Frazier OH *et al,* "*In vivo* evaluation of the HeartWare centrifugal ventricular assist device," Tex Heart Inst J. 2009; 36(2): 186. (sheep)(Transonic Reference # 7922A)

Frazier OH *et al,* "Continuous-flow total artificial heart supports long-term survival of a calf," Tex Heart Inst J. 2009; 36(6): 568-74. (Transonic Reference # 7919A)

Tuzun E *et al,* "Myocardial Hemodynamics, Physiology, and Perfusion with an Axial Flow Left Ventricular Assit Device in the Calf," ASAIO J 2004; 50: 7-53. (Transonic Reference # 2837A)

The Methodist Hospital, Houston, TX

Rodriguez LE *et al,* "Ventricular assist devices (VAD) therapy: new technology, new hope?" Methodist Debakey Cardiovasc J. 2013; 9(1): 32-7. (Transonic Reference # 10183AHR)

Baylor Univ., Houston TX (MicroMed DeBakey Pump)

Noon GP, Loebe M, "Current status of the MicroMed DeBakey Noon Ventricular Assist Device," Tex Heart Inst J. 2010; 37(6): 652-3. (Transonic Reference # 10173AH)

Murai N, Nosé Y *et al,* "Physiological adaptation to a nonpulsatile beventricular assist system," ASAIO J 2003; 49(3): 345-348. (Transonic Reference # 2680A)

Nonaka K, Nosé, Y *et al,* "Development of the Baylor Gyro permanently implantable centrifugal blood pump as a biventricular assist device," Artif Organs 2001; 25(9): 675-82. (Transonic Reference # 2307A)

Fossum TW, Noon GP, Nosé Y, DeBakey ME *et al,* "Complications common to ventricular assist device support are rare with 90 days of DeBakey VAD support in calves," ASAIO J 2001; 47(3): 288-292. (calf, extracorporeal, chronic) (Transonic Reference # 1841A)

Yoskikawa M, Nosé Y *et al,* "Development of the NEDO implantable ventricular assist device with Gyro centrifugal pump," Artif Organs 2000; 24(6): 459-67.(Transonic Reference # 2311A)

Nosé Y, Schima H *et al,* "Development of a Totally Implantable Biventricular Bypass Centrifugal Blood Pump System," Annals of Thoracic Surgery 1999;68(2):775-779. (calf, BVAD) (Transonic Reference # 1511A)

Nakata K, Nosé Y *et al,* "A New Control Method That Estimates the Backflow in a Centrifugal Pump," Artif Organs 1999;23(6): 538-541. (Transonic Reference # 1510A)

Fossum TW, Noon GP, Nosé Y, DeBakey ME *et al,* "Chronic survival of calves implanted with the DeBakey ventricular assist device," Artif Organs 1999; 23(8): 802-6. (Transonic Reference # 2236A)

Tayama E, Noon GP, Nosé Y, DeBakey ME *et al,* "The DeBakey ventricular assist device: current status in 1997," Artif Organs 1999; 23(12): 1113-6. (calf, tubing) (Transonic Reference # 2249A)

Kawahito K, Benkowski R, Noon GP, Nosé Y, Debakey ME *et al,* "*Ex vivo* evaluation of the NASA/DeBakey axial flow ventricular assist device. Results of a 2 week screening test," ASAIO J. 1996; 42(5): M754-7. (Transonic Reference # 711A)

Stony Brook Univ., Stony Brook, NY

Chiu WC *et al,* "Thromboresistance comparison of the HeartMate II ventricular assist device with the device thrombogenicity emulation-optimized HeartAssist 5 VAD," J Biomech Eng. 2014; 136(2): 021014. (Transonic Reference # 10177A)

Girdhar G *et al,* "Device thrombogenicity emulation: a novel method for optimizing mechanical circulatory support device thromboresistance," PLoS One. 2012; 7(3): e32463. (Transonic Reference # 10082A)

University of Utah, Salt Lake City, UT

Stanfield JR, Selzman CH J, "*In vitro* pulsatility analysis of axial-flow and centrifugal-flow left ventricular assist devices." Biomech Eng. 2013; 135(3): 34505.(Transonic Reference # 10178A).

Univ. of CA at Los Angeles, CA

Valdovinos J *et al,* "*In vitro* evaluation of an external compression device for fontan mechanical assistance," Artif Organs. 2014; 38(3): 199-207. (Transonic Reference # 10044A)

Univ. of Louisville, Louisville, Kentucky

Slaughter MS, Koenig SC *et al,* "Intraoperative evaluation of the HeartMate II flow estimator," J Heart Lung Transplant 2009; 28(1): 39-43. Transonic Reference # 7727AH)

Pantalos GM, Koenig SC *et al,* "Effect of continuous and pulsatile flow left ventricular assist on pulsatility in a pediatric animal model of left ventricular dysfunction: pilot observations," ASAIO J. 2007; 53(3): 385-91. (Transonic Reference # 7516A)

Litwak KN, Pantalos GM *et al,* "Ascending aorta outflow graft location and pulsatile ventricular assist provide optimal hemodynamic support in an adult mock circulation," Artif Organs 2005; 29(8): 629-35. (Transonic Reference # 7072A)

Pantalos G, Koenig SC, Gillars KJ, Girdharan GA, Ewert DL, "Characterization of an Adult Mock Circulation for Testing Cardiac Support Devices," ASAIO J 2004; 50:37-46. (Transonic Reference # 2836A)

Koenig SC, Pantalos GM, Gillars KJ, Ewert DL, Litwak KN, Etoch SW, "Hemodynamic and pressure -- volume responses to continuous and pulsatile ventricular assist in a adult mock circulation," ASAIO J 2004; 50: 15-24. (Transonic Reference # 2838AH)

Litwak KN, Koenig S et al, "Pulsatile and continuous flow VAD aortic hemodynamics: Outflow graft location is the key," ASAIO J Abstracts 2003; 49(2): 142. (calf, VAD, aorta, pump outflow) (Transonic Reference # 2675A)

Univ. of Virginia, Charlottesville, VA

Throckmorton A *et al,* "Liquid force predictions and experimental measurements for a magnetically levitated pediatric ventricular assist device," Artif Organs. 2007; 31(5): 359-68. (Transonic Reference # 7425A)

Untaroiu A *et al,* "Computational Design and Experimental Testing of a Novel Axial Flow LVAD," ASAIO J. 2005; 51(6): 702-710. (Transonic Reference # 7175A

Pennylvania State University

Lukic B *et al,* "The effect of left ventricular function and drive pressures on the filling and ejection of a pulsatile pediatric ventricular assist device in an acute animal model," ASAIO J 2007; 53(3): 379-84. (Transonic Reference # 7404A)
Roszelle BN *et al,* "The 12 cc Penn State

pulsatile pediatric ventricular assist device: flow field observations at a reduced beat rate with application to weaning," ASAIO J. 2008; 54(3): 325-31. (Transonic Reference # 7663A)

Son HS *et al,* "Ventricular Assist Device Implantation Using a Right Thoracotomy," ASAIO J 2006; 52(4): 386-390. (Transonic Reference # 7292A)

Lerner Research Institute, Cleveland, Ohio

Ootaki Y *et al,* "Initial *In Vivo* Evaluation of the DexAide Right Ventricular Assist Device," ASAIO J 2005; 51(6): 739-42. (Transonic Reference # 7171A)

Fukamachi K *et al,* "Development of a small implantable right ventricular assist device," ASAIO J. 2005; 51(6):730-5. (Transonic Reference # 71699A)

Schenk S *et al,* "*In vivo* performance and biocompatibility of the MagScrew ventricular assist device," ASAIO Journal, 2003; 49:(5) 594-598. (Transonic Reference # 2681A)

Ohtsuka G, Nosé Y *et al,* "An emergency balloon occlusion system for a rotary blood pump left ventricular assist system," Artif Organs 1999; 23(8): 704-7. (Transonic Reference # 2310A)

Massiello A *et al,* "The Cleveland Clinic-Nimbus total artificial heart. Design and in vitro function," J Thorac Cardiovasc Surg. 1994;108(3): 412-9.

Weber S *et al,* "*In vitro* controllability of the MagScrew total artificial heart system," ASAIO J 2002; 48(6): 606-11. (Transonic Reference # 2490A)

The Cleveland Clinic, Cleveland, OH

Duncan BW, "Pediatric Mechanical Circulatory Support," ASAIO J. 2005;51(6): ix-xiv. (Transonic Reference # 7164AH)

University of Rochester, Rochester, NY

Schwarz KQ *et al,* "Non-invasive flow measurement of a rotary pump ventricular assist device using quantitative contrast echocardiography," J Am Soc Echocardiogr. 2010; 23(3): 324-9. (Transonic Reference # 7938A) Univ. Rochester Medical Center, Rochester, NY, USA. karl_schwarz@urmc.rochester.edu

Univ. of Maryland, Baltimore, MD

Sorensen EN, Griffith BP *et al,* "University of Maryland surgical experience with the Jarvik 2000 axial flow ventricular assist device," Ann Thorac Surg. 2012 Jan;93(1):133-40. (Transonic Reference # 10186AG)

Kilic A *et al,* "Early in vivo experience with the pediatric Jarvik 2000 heart," ASAIO J. 2007; 53(3): 374-8. (Transonic Reference # 7405)

Univ. of Michigan Health System, Ann Arbor, MI

Haft J *et al,* "Design of an artificial lung compliance chamber for pulmonary replacement," ASAIO J 2003; 49(1): 35-40. (Transonic Reference # 2674A)

Univ. of Pittsburgh, Pittsburgh, PA

Litwak KN, Griffith BP *et al,* "Effects of continuous flow left ventricular assist device support on skin tissue microcirculation and aortic hemodynamics," ASAIO J 2003; 49(1):103-107. (Transonic Reference # 2683A)

Snyder TA *et al,* "Platelet activation, aggregation, and life span in calves implanted with axial flow ventricular assist devices," Ann Thorac Surg 2002; 6: 1933-8. (Transonic Reference # 2545A)

Thermo Cardiosystems Inc. Woburn, MA

Loree HM *et al,* "The Heartmate III: design and in vivo studies of a maglev centrifugal left ventricular assist device," Artif Organs 2001; 25(5): 386-91, 2001. (Transonic Reference # 2305A)

Kriton Medical, Inc., Citrus Heights, CA

Wampler R *et al,* "A sealless centrifugal blood pump with passive magnetic and hydrodynamic bearings," Artif Organs 1999; 23(8): 780-4. (Transonic Reference # 2304A)

JAPAN
Cardiovascular Center Research Institute, Osaka

Ohnuma K *et al,* "Development of a flow rate monitoring method for the wearable ventricular assist device driver," J Artif Organs. 2014 Dec 13. (Transonic Reference # 10174)

Tatsumi E *et al,* "*In vivo* evaluation of the national cardiovascular center eletrohydraulic total artificial heart," Artif Organs 1999; 23(3): 242-8. (Transonic Reference # 2303A)

Nakamura M *et al,* "The development of a control method for a total artificial heart using mixed venous oxygen saturation," Artif Organs 1999; 23(3): 235-41. (Transonic Reference # 2302A)

The University of Tokyo, Tokyo, Japan

Umeki A *et al,* "Change of coronary flow by continuous-flow left ventricular assist device with cardiac beat synchronizing system (native heart load control system) in acute ischemic heart failure model," Circ J. 2013; 77(4): 995-1000. (Transonic Reference # 10184A)

Denki University, Saitama, Japan

Miyawaki F *et al,* "Evaluation of recovery directed left ventricular assist device using isolated perfused rabbit hearts," ASAIO J. 2004; 50(4):316-20. (Transonic Reference # 2931A)

Univ. of Tsukuba, Tsukuba, Ibaraki

Kosaka R, Nosé Y *et al,* "Operating point control system for a continuous flow artifical heart: In vitro study," ASAIO J 2003;49(3):259-64. (pump, tubing, extracorporeal) (Transonic Reference # 2309A)

Tohoku University, Sendai

Yambe T *et al,* "A future prediction type artificial heart system," Artif Organs 1999; 23(3): 268-73. (Transonic Reference # 2301A)

Kyushu University, Fukuoka

Nakano T *et al,* "Impacts of pulsatile systemic circulation on endothelium-derived nitric oxide release in anesthetized dogs," Ann Thorac Surg 2001; 72(1): 156-62. (Transonic Reference # 2130A)

REPUBLIC OF CHINA
National Taiwan University, Taipei, Taiwan

Chou NK *et al,* "Physiologic analysis of cardiac cycle in an implantable impeller centrifugal left ventricular assist device," Artif Organs 2001; 25(8): 613-6. (Transonic Reference # 2314A)

Chou NK *et al,* "Development of a totally implantable pulsatile centrifugal pump as a ventricular assist device," Artif Organs 2001; 25(8): 603-6. (Transonic Reference # 2308A)

KOREA
Seoul National University, Seoul

Chung, JMin BG *et al,* "Hydrodynamic and static performance evaluation of the moving-actuator type biventricular assist device, AnyHeart," ASAIO J 2003; 49(5): 599-603. (Transonic Reference # 2678A)

AUSTRIA
Medical University of Vienna, Vienna
Voitl P, Schima H *et al,* "Coronary hemodynamics and myocardial oxygen consumption during support with rotary blood pumps," Artif Organs 2009; 33(1): 77-80 (Transonic Reference # 7735A)

Moscato F, Schima H *et al,* "Left ventricular pressure-volume loop analysis during continuous cardiac assist in acute animal trials," Artif Organs 2007; 31(5): 369-76, (Transonic Reference # 7426A)

SWITZERLAND
Institute for Dynamic Systems and Control, Zurich,
Amacher R *et al,* "A novel interface for hybrid mock circulations to evaluate ventricular assist devices," IEEE Trans Biomed Eng. 2013; 60(2): 507-16. (Transonic Reference # 10166A)

Centre Hospitalier Universitaire Vaudois CHUV, Lausanne,
Huber CH, von Segesser LK *et al,* "No drive line, no seal, no bearing and no wear: magnetics for impeller suspension and flow assessment in a new VAD," Interact Cardiovasc Thorac Surg. 2004; 3(2): 336-40. (Transonic Reference # 7492A)

Tevaearai HT, "Performance of a new implantable cardiac assist centrifugal pump." Artif Organs. 2001; 25(1): 67-9. (Transonic Reference # 1808)

THE NETHERLANDS
University of Groningen
Mihaylov D *et al,* "Evaluation of the optimal driving mode during left ventricular assist with pulsatile catheter pump in calves," Artif Organs 1999; 23(12):1117-22. (Transonic Reference # 2306A)

Eindhoven University of Technology,
Bozkurt S *et al,* "Improving arterial pulsatility by feedback control of a continuous flow left ventricular assist device via in silico modeling." Int J Artif Organs. 2014; 37(10): 773-85 Transonic Reference # 10179A).

Academic Medical Ctr,Amsterdam
Pennings KA et al, "Pump flow estimation from pressure head and power uptake for the HeartAssist5, HeartMate II, and HeartWare VADs," ASAIO J. 2013; 59(4): 420-6. (Transonic Reference # 11213A)

GERMANY
Univ. of Leipzig Heart Center, Leipzig
Thiele H *et al,* "Reversal of cardiogenic shock by percutaneous left atrial-to-femoral arterial bypass assistance," Circulation. 2001;104(24):2917-22. (Transonic Reference # 2362AH)

University Hospital Charité, Humboldt University, Berlin
Linneweber J, Nosé Y *et al,* "Hemodynamic exercise response in calves with an implantable biventricular centrifugal blood pump," Artif Organs 2001; 25(12): 1018-21. (Transonic Reference # 2270A)

Heart and Vascular Center Duisburg, Duisburg
Spiliopoulos S *et al,* "Beneficial aspects of real time flow measurements for the management of acute right ventricular heart failure following continuous flow ventricular assist device implantation," J Cardiothorac Surg. 2012 7: 119. (Transonic Reference # 10208A)

TURKEY
Sisli Florence Nightingale Hospital, Istanbul
Pektok E *et al,* "Remote monitoring of left ventricular assist device parameters after HeartAssist-5 implantation," Artif Organs. 2013; 37(9): 820-5. (Transonic Reference # 10181A)

AUSTRALIA
Univ. of Queensland, Prince Charles Hospital, Brisbane
Stevens MC, Timms D *et al,* "Physiological control of dual rotary pumps as a biventricular assist device using a master/slave approach,"Artif Organs. 2014; 38(9): 766-74. (Transonic Reference # 10180A)

Gregory SD Timms D, "A Compliant, Banded Outflow Cannula for Decreased Afterload Sensitivity of Rotary Right Ventricular Assist Devices," Artif Organs. 2014 Jul 9. (Transonic Reference # 10175A)

Stevens MC, Fraser JF, Timms D *et al,* "*In vitro* and *in vivo* characterization of three different modes of pump operation when using a left ventricular assist device as a right ventricular assist device," Artif Organs. 2014; 38(11): 931-9. (Transonic Reference # 10040A)

Nestler F, Bradley AP, Wilson SJ, Timms DL, "Modeling of a Rotary Blood Pump," Artif Organs. 2014; 38(3): 182-190. (Transonic Reference # 10039A)

Stevens MC, Fraser JF *et al,* "Frank-starling control of a left ventricular assist device," Conf Proc IEEE Eng Med Biol Soc. 2011; 2011:1335-8. (Transonic Reference # 10185A)

BRAZIL
Faculdade de Medicina da Universidade de São Paulo
Succi GM, Stolf NA *et al,* "Cavopulmonary anastomosis improves left ventricular assist device support in acute biventricular failure," Eur J Cardiothorac Surg. 2009; 35(3): 528-33 (Transonic Reference # 7742A)

TURKEY
Dept. of Heart Transplant and Mechanical Circulatory Support, Sisli Florence Nightingale Hospital, Istanbul
Demirozu ZT, Arat N, Kucukaksu DS, "Fine-tuning management of the Heart Assist 5 left ventricular assist device with two- and three-dimensional echocardiography," "Cardiovasc J Afr. 2016; 27(4): 208-212. (Transonic Reference # 11201AH)