The Proceedings of the Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

May 18–20, 2006
The Holiday Inn on King
Toronto, Ontario, Canada

Honorary Chairs
Aydin Aytaç, MD • William S. Pierce, MD • John A. Waldhausen, MD • William G. Williams, MD

Program Co-chairs
Sabine H. Däbritz, MD • Brian W. Duncan, MD • Roland Hetzer, MD, PhD
John L. Myers, MD • Gerson Rosenberg, PhD
Akif Ündar, PhD • Ross M. Ungerleider, MD • Glen S. Van Arsdell, MD

Editor: Akif Ündar, PhD

A continuing education service of Penn State College of Medicine
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### The Holiday Inn on King

![Holiday Inn on King Map](image)

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- TERRACE
- ESCALATOR
- HOT OFFICE
- COAT CHECK
- STAIRS
Welcome to the Second Annual Event

Akif Ündar, Ph.D., Conference Founder
Departments of Pediatrics, Surgery, and Bioengineering, Penn State College of Medicine, Penn State Children’s Hospital, Hershey, Pennsylvania, U.S.A.

On the behalf of the organizers of the Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion, I would like to welcome you to the Second Annual Event at the Holiday Inn on King, Toronto, Ontario, Canada, May 18-20, 2006.

The primary objective of the Second Annual Event is to explicitly describe the problems with current pediatric mechanical circulatory support systems, methods, and techniques during acute and chronic support. In order to solve these problems or suggest potential solutions, several leading pediatric cardiac surgeons, pediatric cardiologists, basic scientists, engineers, nurses, and pediatric perfusionists will participate as invited lecturers.

Resembling the First Conference, the Second Annual Event will have three phases.

First Phase: Leading clinicians, engineers, basic scientists, and perfusionists will describe the current devices and techniques currently in use. In particular, advantages as well as limitations of these devices and techniques will be described in detail in several Plenary Sessions and Mini-Symposiums during the conference.

Second Phase: Pediatric circulatory support devices currently in the development stage will be described. Novel research projects related to proteomics and nanotechnology will be included.

Third Phase: All manuscripts from the presenters will be peer reviewed and published as a block in the September-October 2006 issue of the ASAIO Journal. This issue of the ASAIO Journal is dedicated to our Second International Conference.

These three phases are identical to those we had in our First International Event.1,2 However, there will be a slight difference between these two events. At last year’s event, only a couple of junior faculty participated as invited speakers. For this year’s event, approximately one-fourth of all invited speakers are junior investigators. The members of the Scientific Committee invited junior faculty based on their high-quality publications and novelty of their research projects and results.

The Second Annual Event is truly an international meeting with participants from all over the world, including Australia, Belgium, Canada, China, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, Spain, South Korea, Taiwan, Turkey, The United Kingdom, and the United States.

Major financial support is provided by the Penn State Children’s Hospital and the Penn State College of Medicine. In particular, the Departments of Pediatrics, Surgery, and Bioengineering in addition to the office of Continuing Education of the Penn State College of Medicine have been instrumental in organizing this event.

Once again, I welcome each of you to this unique international conference. If the course of just one child is improved as a result of this event, we have reached our goal.

REFERENCES:
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

Scientific Committee

Honorary Chairs
Aydın Aytac, MD
Professor Emeritus
V.K.V. American Bristol Hospital
Istanbul, Turkey

William S. Pierce, MD
Professor Emeritus
Evan Pugh Professor of Surgery
Penn State College of Medicine
Hershey, PA, USA

John A. Waldhausen, MD
Professor Emeritus
Founding Chairman of Surgery
Penn State College of Medicine
Hershey, PA, USA

William G. Williams, MD
Professor Emeritus
The Hospital for Sick Children
Toronto, ON, Canada

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Department of Cardiac Surgery
University Hospital LMU Grosshadern
Munich, Germany

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Children’s Hospital
Cleveland Clinic Foundation
Cleveland, OH, USA

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Deutsches Herzzentrum Berlin
Berlin, Germany

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Penn State College of Medicine
Hershey, PA, USA

Gerson Rosenberg, PhD
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Akif Ündar, PhD
Department of Pediatrics, Surgery and Bioengineering
Penn State College of Medicine
Penn State Children’s Hospital
Hershey, PA, USA

Ross M. Ungerleider, MD
Oregon Health and Sciences University
Doernbecher Children’s Hospital
Portland, OR, USA

Glen S. Van Arsdell, MD
Department of Cardiac Surgery
The Hospital for Sick Children
Toronto, ON, Canada
Endorsements

American Society for Artificial Internal Organs

Conference Sponsors

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The National Heart, Lung and Blood Institute grant application is pending approval
Final Scientific Program

**Wednesday, May 17, 2006**

5–10 pm  Registration/Speaker Ready Room Open

**Thursday, May 18, 2006**

7:00 am Registration/Breakfast/Speaker Ready Room Open

8:00  Welcome  
John L. Myers, MD, Hershey, PA, USA; Akif Ündar, PhD, Hershey, PA, USA

8:10  **PLENARY SESSION #1**  
Principles, Practices, and Outcomes of CPB in Neonates and Infants  
Co-chairs: Aydin Aytaç, MD, Istanbul, Turkey; Ross Ungerleider, MD, Portland, OR, USA;  
William G. Williams, MD, Toronto, ON, Canada

**INVITED LECTURES**

- Cerebral Protection in Neonates and Infants  
  Francis Fynn-Thompson, MD, Boston, MA, USA

- Endotoxin Preconditioning: Robust Brain Protection during Infant CPB through Genetic Reprogramming  
  Edward Hickey, MD, London, UK

- Circuit Miniaturization on the Systemic Inflammatory Process in Neonatal CPB: The Experimental Findings  
  Tara Karamlou, MD, Toronto, ON, Canada

- Myocardial Protection  
  Bradley S. Allen, MD, Houston, TX, USA

- Assessment of Mortality Rates  
  Karl F. Welke, MD, Portland, OR, USA

9:40  **NEW TECHNOLOGY**  
The Use of Mass Spectrometry in Managing Stage 1 Hypoplastic Left Heart Syndrome Palliation  
Glen S. Van Arsdell, MD, Toronto, ON, Canada

Moderator: John L. Myers, MD, Hershey, PA, USA

10:00  Break/Exhibits/Posters

10:30  **SPECIAL LECTURE #1**  
Systemic Inflammation Related to Cardiac Operations in Neonates and Infants  
Marie-Christine Seghaye, MD, Aachen, Germany

Moderator: Ross Ungerleider, MD, Portland, OR, USA
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

11:10  KEY NOTE LECTURE #1
Past, Present, and Future of Pediatric Cardiac Surgery Practices in a Developing Country: The Turkish Experience
Aydın Aytaç, MD, Istanbul, Turkey
Introduction: Akif Ündar, PhD, Hershey, PA, USA

12:00 noon  Lunch

1:00 pm  PLENARY SESSION #2
Mechanical Circulatory Support Systems
Co-chairs: Sabine H. Däbritz, MD, Munich, Germany; William S. Pierce, MD, Hershey, PA, USA; Glen S. Van Arsdell, MD, Toronto, ON, Canada

INVITED LECTURES
• Routine Ventricular Assist Following Norwood Procedure
Ross Ungerleider, MD, Portland, OR, USA
• Pediatric Mechanical Circulatory Support in Japan and Development of Tiny Rotary Blood Pump
Shunji Sano, MD, PhD, Okayama, Japan
• Pediatric Mechanical Circulatory Support in Europe
Brigitte Stiller, MD, PhD, Berlin, Germany; Roland Hetzer, MD, PhD, Berlin, Germany
• Pediatric Mechanical Circulatory Support in the United States
Brian Duncan, MD, Cleveland, OH, USA
• Emergency Use of Pediatric Circulatory Support
Kirk R. Kanter, MD, Atlanta, GA, USA
• Management of Pediatric Patients after VAD Implantation
Brigitte Stiller, MD, PhD, Berlin, Germany

3:30  Break/Exhibits/Posters

4:00  MINI-SYMPOSIUM #1
ABCs of ECMO in Pediatric Patients
Co-chairs: Jennifer Hirsch, MD, Ann Arbor, MI, USA; Billie Lou Short, MD, Washington, DC, USA

INVITED LECTURES
• Cannulation, Techniques, Devices, and Management
Jennifer Hirsch, MD, Ann Arbor, MI, USA
• Cardiac Support
Jennifer Hirsch, MD, Ann Arbor, MI, USA
• Respiratory Support
Billie Lou Short, MD, Washington, DC, USA
• Automatic Suction Control in Pediatric ECMO
Bart Meyns, MD, PhD, Leuven, Belgium
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- Clinical Outcomes and Experience of 12 Children Managed Extracorporeal Membrane Oxygenation in Fuwai Hospital
  Long Cun, MD, Beijing, China

5:45–7:45  WINE AND CHEESE

MODERATED POSTER PRESENTATION SESSION #1

Pediatric Cardiac Assist Devices/Pediatric Heart-Lung Transplantation/ECMO/CPB

Co-Chairs: Ulrich Steinseifer, PhD, Aachen, Germany; Karl F. Welke, MD, Portland, OR, USA

Moderator: Ulrich Steinseifer, PhD

P1. Experience with Pediatric LVAD Support
   Christof Schmid, MD, Muenster, Germany

P2. Utilization of the Berlin Heart as a Bridge to Transplantation in Pediatric Patients
   Peter D. Wearden, MD, Pittsburgh, PA, USA

P3. Sub Cutaneous Low Molecular Weight Heparin for Management of Anticoagulation in Infants on Excor Ventricular Assist Device
   Olivier Ghez, MD, London, UK

P4. Complex Transport of a Hurricane Katrina Evacuee on BiVAD Support
   Richard Owens, CCP, Houston, TX, USA

P5. Left Ventricular Assist Device for Pediatric Postcardiotomy Cardiac Failure
   De-ming Zhu, MD, Shanghai, China

P6. Mechanical Heart Valve Performance in a Pulsatile Pediatric Ventricular Assist Device
   Conrad M. Zapanta, PhD, Hershey, PA, USA

P7. Heart Transplantation in Grown-up Congenital Heart Disease Patients
   K. Oguz Coskun, MD, Bad Oeynhausen, Germany

P8. Result of Pediatric Cardiac Transplantation with or without Bridge Methods
   Nai-Hsin Chi, MD, Taipei, Taiwan

   Shye-Jao Wu, MD, MS, Taipei, Taiwan

    Julia Reckers, MD, Sankt Augustin, Germany

Moderator: Karl F. Welke, MD

P11. DIDECIMO: A New Polymethyl Pentene Oxygenator for Pediatric ECMO
     Guiseppe Ciccarello, CCP, Taormina, Messina, Italy

P12. Use of a Novel Anticoagulation Strategy during ECMO in Pediatric Population: Single Center Experience
     Salvatore Agati, MD, Taormina, Messina, Italy
P.13. Rapid, Bedside Quantification of Recirculation during Venovenous ECMO for Optimizing Oxygen Delivery
Edward Darling, MS, CCP, Syracuse, NY, USA

Basil M. Henrick, LCCP, ECCP, Dublin, Ireland

P.15. Modified CPB Circuit for Postoperative Rescue of High-Risk Patients Following Cardiac Repair: Are We Keeping Safe?
Christian Pizarro, MD, Wilmington, DE, USA

P.16. Aristotle Score Predicts Outcome in Patients Requiring Extracorporeal Circulatory Support Following Repair of Congenital Heart Disease
Christopher D. Derby, MD, Wilmington, DE, USA

P.17. The Effect of Flow Rate, Negative Pressure, and Duration of Modified Ultrafiltration on Hemodynamics and Inflammatory Mediators
Wei Wang, MD, PhD, Shanghai, China

Yasuhiro Kotani, MD, Okayama, Japan

P.19. Postoperative Prophylactic Peritoneal Dialysis in Neonates and Infants after Complex Congenital Cardiac Surgery
Tijen Alkan, MD, Istanbul, Turkey

P.20. Anoxic Ventilation Improves Systemic Perfusion during Extracorporeal Circulation with Uncontrolled Systemic-to-Pulmonary Shunt
James M. Hammel, MD, Omaha, NE, USA

Friday, May 19, 2006

7:00 am Registration/Continental Breakfast
8:00 PLENARY SESSION #3
Novel Pediatric Heart Pumps under Development
Co-chairs: Tim Baldwin, PhD, NHLBI, Bethesda, MD, USA; Roland Hetzer, MD, PhD, Berlin, Germany; Gerson Rosenberg, PhD, Hershey, PA, USA

INVITED LECTURES
• The Need for New Pediatric Heart Pumps for Chronic Use in the United States
Tim Baldwin, PhD, NHLBI, Bethesda, MD, USA

• Current Progress in the Development of the PediaFlow™ Pediatric Ventricular Assist Device
Harvey Borovetz, PhD, Pittsburgh, PA, USA

• The Penn State Pulsatile Pediatric VAD
William Weiss, PhD, Hershey, PA, USA
Second International Conference on **Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion**

- **Infant and Child-Size Jarvik 2000 Hearts**
  Robert Jarvik, MD, New York, NY, USA

- **Surface Modifications of Hollow Fiber Membranes as Applied to the Ension pCAS System**
  Mark Gartner, MS, Pittsburgh, PA, USA

- **The PediPump: A Versatile, Implantable, Pediatric Ventricular Assist Device**
  Brian Duncan, MD, Cleveland, OH, USA

10:00 
Break/Exhibits/Posters

10:30  
**SPECIAL LECTURE #2**
Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS): Implications of a National VAD Registry in Pediatrics
Elizabeth D. Blume, MD, Boston, MA, USA
Moderator: Brian Duncan, MD, Cleveland, OH, USA

10:55  
**SPECIAL LECTURE #3**
Proteomics and Pediatric Cardiac Surgery
Kent Vrana, PhD, Hershey, PA, USA
Moderator: Marie-Christine Seghaye, MD, Aachen, Germany

11:20  
**KEY NOTE LECTURE #2**
The Early Years: Adventure and Misadventure!
William G. Williams, MD, Toronto, ON, Canada
Introduction: Glen S. Van Arsdell, MD, Toronto, ON, Canada

12:10 pm  
Lunch

1:00  
**PLENARY SESSION #4**
Pediatric Heart Transplantation
Co-chairs: Elizabeth D. Blume, MD, Boston, MA, USA; Kirk R. Kanter, MD, Atlanta, GA, USA; Shunji Sano, MD, PhD, Okayama, Japan

**INVITED LECTURES**
- North American Trends in Perioperative Pediatric Transplantation
  Glen S. Van Arsdell, MD, Toronto, ON, Canada

- Pediatric Heart Transplantation in Europe
  Christoph Knosalla, MD, PhD, Berlin, Germany; Roland Hetzer, MD, PhD, Berlin, Germany

- Use of Mechanical Cardiac Assistance in Cardiac Transplantation: Evolving Practice
  Carin van Doorn, MD, FRCS, London, UK

- Long-Term Outcome of Thoracic Transplantation in Pediatric Patients (and GUCH Patients)
  Sabine H. Däbritz, MD, Munich, Germany
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SLIDE PRESENTATIONS

- **Outcome of Heart Transplantation in 95 Pediatric Recipients**
  K. Oguz Coskun, MD, BadOeynhausen, Germany

- **Use of Extracorporeal Membrane Oxygenation (ECMO) as a Bridge to Pediatric Heart Transplantation**
  Anne Dipchand, MD, Toronto, ON, Canada

3:00 Break/Exhibits/Posters

3:30–6:00 REGULAR SLIDE PRESENTATION #1

**Mechanical Circulatory Support Systems/ECMO/CPB**

Co-Chairs: Brian Duncan, MD, Cleveland, OH, USA; Kyung Sun, MD, PhD, South Korea; William Weiss, PhD, Hershey, PA, USA

Moderator: Brian Duncan, MD

- **High-Risk Medical Devices, Children and the F.D.A.: Regulatory Challenges Facing Pediatric Circulatory Support Devices**
  Christopher Almond, MD, MPH, Boston, MA, USA

- **Coagulation Management in Pediatric Mechanical Circulatory Support**
  Thorsten Drews, MD, Berlin, Germany

- **Pulsatile ECMO and VAD: A Dual Use of a New Device in Pediatric Cardiac Patients**
  Salvatore Agati, MD, Taormina, Messina, Italy

- **Effects of Pulsatile and Nonpulsatile Perfusion on Vital Organ Recovery in Pediatric Heart Surgery: A Pilot Clinical Study**
  Tijen Alkan, MD, Istanbul, Turkey

Moderator: Kyung Sun, MD

- **Seven Years’ Experiences of Pediatric Cardiopulmonary Bypass: 8685 Cases in Shanghai Children’s Medical Center**
  Wei Wang, MD, PhD, Shanghai, China

- **Normothermic Bypass in Pediatric Surgery: Technical Aspect and Clinical Experience About 1400 Cases**
  Yves Durandy, MD, Massy, Ile de France, France

- **Atrial Natriuretic Peptide: Could It Be a Marker for Postoperative Recurrent Effusions after Fontan Circulation in Complex Congenital Heart Defects?**
  Tijen Alkan, MD, Istanbul, Turkey

- **Continuous Cerebral and Myocardial Perfusion during Aortic Arch Repair**
  Yasuhiro Kotani, MD, Okayama, Japan

Moderator: William Weiss, PhD

- **Novel ‘Biomechanical’ Polymeric Valve Prostheses with Special Design for Aortic and Mitral Position: A Future Option for Pediatric Patients**
  Joerg S. Sachweh, MD, Aachen, Germany
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- Development of a Pneumatically-Driven Pump-Lung for Rescue Applications
  Christina Feldmann, PhD, Aachen, Germany

- Feasibility of Trans-Hepatic Left Atrial Cannulation for Placement of a Pediatric Percutaneous Ventricular Assist Device
  Jeffrey G. Gossett, MD, Ann Arbor, MI, USA

- In Vivo Testing of the Levitronix Pediatric VAS
  Peter D. Wearden, MD, Pittsburgh, PA, USA

6:15–7:15 MODERATED POSTER PRESENTATION SESSION #2

Pediatric Cardiopulmonary Bypass/Engineering Approaches
Co-chairs: Salvatore Agati, MD, Taormina, Italy; Keefe Manning, PhD, University Park, PA, USA
Moderator: Keefe Manning, PhD

P.1. Computational Flow and Mass Transfer Analysis of a Pediatric Pump-Oxygenator
  Mark Gartner, ME, Pittsburgh, PA, USA

P.2. Computational Fluid Dynamics Evaluation of Steady and Pulsatile Hemodynamic Performance of Pediatric Aortic Cannulae
  Eric G. Paterson, PhD, University Park, PA, USA

P.3. 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
  Branka Lukic, MS, Hershey, PA, USA

P.4. Anticoagulation Monitoring in Juvenile Sheep and Goats
  Tigran Khalapyan, MD, Hershey, PA, USA

P.5. Extracorporeal Membrane Oxygenation Support for Severe Congenital Trachea Stenosis
  Shu-Chien Huang, Taipei, Taiwan; WenJe Ko, Taipei, Taiwan

P.6. Comparison of the Coronary Artery Blood Flow between Pulsatile Pump and Non-Pulsatile Pump Accompanying Intraaortic Balloon Pump in Extracorporeal Circulation
  Ho Sung Son, Seoul, South Korea

P.7. Comparison of Perfusion Modes in Terms of Surplus Hemodynamic Energy Levels in a Simulated Neonatal CPB Model
  Akif Ündar, PhD, Hershey, PA, USA

P.8. Comparison of Hollow Fiber Membrane Oxygenators with Different Perfusion Modes during Normothermic and Hypothermic CPB in a Simulated Neonatal Model
  Bingyang Ji, MD, Hershey, PA, USA
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P9. Closed Chest Cardiopulmonary Bypass to Facilitate Giant Intracranial Aneurysm Clipping in a Pediatric Patient: Future Anesthetic and Neuromonitoring Considerations  
**Kenneth J. Saliba, DO, Hershey, PA, USA**

P10. Transcranial Doppler Revealed Retrograde Cerebral Artery Flow during Norwood 1 Operation  
**Stephen J. Kimatian, MD, FAAP, Hershey, PA, USA**

Unmoderated Presentations

P11. Acute Myocardial Infarction in Young Adult. A Case Report and Literature Review  
**K. Oguz Coskun, MD, BadOeynhausen, Germany**

P12. Commerrel Diverticulum: Case Report and Surgical Approach to Vascular Rings  
**Tijen Alkan, MD, Istanbul, Turkey**

P13. Follow-Up of Pediatric Patients with Kawasaki Disease and a Case Report of Kitamura Operation  
**K. Oguz Coskun, MD, BadOeynhausen, Germany**

P14. Shprintzen (Velo-cardio-facial) Syndrome: A Rare Case  
**Tijen Alkan, MD, Istanbul, Turkey**

**K. Oguz Coskun, MD, BadOeynhausen, Germany**

**Tijen Alkan, MD, Istanbul, Turkey**

7:30–10:00 pm **GALA DINNER: AWARDS RECOGNITION**  
Moderators: William Pierce, MD, Hershey, PA, USA; Gerson Rosenberg, PhD, Hershey, PA, USA

**Saturday, May 20, 2006**

7:00 am  
Continental Breakfast

8:00 **MINI-SYMPOSIUM #2**  
Engineering Aspects of Pediatric Heart Pumps and Oxygenators  
Co-chairs: Yukihiko Nose, MD, PhD, Houston, TX, USA; Gerson Rosenberg, PhD, Hershey, PA, USA  

**INVITED LECTURES**  
- Design and Engineering Aspects of Pediatric Support Devices: An Update  
  Ulrich Steinseifer, PhD, Aachen, Germany
- Cannula Designs for Pediatric VADs  
  Gerson Rosenberg, PhD, Hershey, PA, USA
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- Development and Application of the Levitronix Mag-Lev Technology for Pediatric Circulatory Support
  Kurt Dasse, PhD, Waltham, MA, USA

- Development of a Tiny Centrifugal Rotary Blood Pump “Tiny Pump” for Pediatric Super-Mini CPB, ECMO, and Ventricular Assistance
  Setsuo Takatani, PhD, DMed, Tokyo, Japan

- Hollow Fiber Oxygenator for Pediatric Application
  Yukihiko Nose, MD, PhD, Houston, TX, USA

9:15 **MINI-SYMPOSIUM #3**

Pulsatile versus Non-Pulsatile Flow during Acute and Chronic Cardiac Support
Co-chairs: Peer M. Portner, PhD, Palo Alto, CA, USA; Akif Ündar, PhD, Hershey, PA, USA

**INVITED LECTURES**

- Physiology of Pulsatile Flow during Chronic Support
  Peer Portner, PhD, Palo Alto, CA, USA

- Use of Pulsatile Flow during ECMO
  Carmelo Mignosa, MD, Taormina, Italy

- The North American Experience with the Berlin Heart Pump
  Johannes Müller, MD, Berlin, Germany

- Guidelines for the Use of Pulsatile Flow During CPB in Neonates and Infants
  Akif Ündar, PhD, Hershey, PA, USA

10:15 Breaks/Exhibits/Posters

10:45 **SPECIAL LECTURE #4**

Microfluidic Devices for Continuous Blood Plasma Separation and Analysis during Pediatric Cardiac Surgery
Jeffrey D. Zahn, PhD, University Park, PA, USA; Sung Yang, MS, University Park, PA, USA

Moderator: Kent Vrana, PhD, Hershey, PA, USA

11:10 **KEY NOTE LECTURE #3**

Lessons Learned (But Forgotten?) in the Development of Pediatric Cardiopulmonary Assist Devices
Harvey Borovetz, PhD, Pittsburgh, PA, USA

Introduction: Gerson Rosenberg, PhD, Hershey, PA, USA

12:00 noon Lunch

1:00 pm **MINI-SYMPOSIUM #4**

Perfusion Aspects of Pediatric Cardiac Surgery
Co-Chairs: Long Cun, MD, Beijing, China; Carmen Giacomuzzi, CCP, Portland, OR, USA

**INVITED LECTURES**

- HIT or MYTH: What is the Real Story Behind Pediatric HIT?
  Carmen Giacomuzzi, CCP, Portland, OR, USA
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- Rescue ECMO in Children
  Colleen Gruenwald, MHSc, RN, CCP, CPC, Toronto, ON, Canada
- Modified Ultrafiltration (MUF) in Pediatric Cardiopulmonary Bypass
  Edward Darling, MS, CCP, Syracuse, NY, USA

2:00 MINI-SYMPOSIUM #5
Blood Rheology
Moderator: Akif Ündar, PhD, Hershey, PA, USA

INVITED LECTURES
- Hemorheology of Blood Damage in Heart-Assist Devices
  Marina V. Kameneva, PhD, Pittsburgh, PA, USA
- Blood Rheology and PVAD Performance: In-vitro and Animal Models and the Problem of Human Performance Prediction
  Steven Deutsch, PhD, University Park, PA, USA

2:30 REGULAR SLIDE PRESENTATIONS #2
Cardiopulmonary Bypass/Computational Fluid Dynamics/Blood Rheology/Pulsatile Flow
Co-Chairs: Steven Deutsch, PhD, University Park, PA, USA; Carmelo Mignosa, MD, Taormina, Italy; Setsuo Takatani, PhD, DMS, Tokyo, Japan

- Computational Fluid Dynamics and Experimental Characterization of a Miniature Maglev Ventricular Assist Device (VAD) for Children and Adults
  Zhongjun J. Wu, PhD, Baltimore, MD, USA
- Initial Experience with the Development and Numerical Analysis for a Low-Pressure Artificial Right Ventricle for Pediatric Fontan Patients
  Rui Wang, MS, Boulder, CO, USA
- Development of Standard Tests to Examine Viscoelastic Properties of Blood of Experimental Animals for Pediatric Mechanical Support Device Evaluation
  Philip Marascalco, Pittsburgh, PA, USA
- Hemodynamic Energy Generated in Combining a Centrifugal Pump with an Intraaortic Balloon Pump
  Choon Hak Lim, MD, Seoul, South Korea
- Effect of Continuous and Pulsatile Flow Left Ventricular Assist on Pulsatility in a Pediatric Animal Model of Left Ventricular Dysfunction: Early Results
  George Pantalos, PhD, Louisville, KY, USA
- A Model of “pCO₂ gap” during Hypothermic Cardiopulmonary Bypass
  Greg A. Johnson, PhD, Pittsburgh, PA, USA
- Mechanical Efficiency of Centrifugal Pumps Used in ECMO and Ventricular Assist
  Mark Henderson, CCP, Cleveland, OH, USA

4:00 Program Evaluation and Adjournment
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

International Scientific Committee (Final)

Salvatore Agati, MD, Italy
Atif Akcevin, MD, Turkey
Tijen Alkan, MD, Turkey
Bradley S. Allen, MD, USA
Christopher Almond, MD, MPH, USA
Aydin Aytac, MD, Turkey
Larry Baer, CCP, USA
Tim Baldwin, PhD, USA
Ute Blanz, MD, Germany
Elizabeth D. Blume, MD, USA
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Nai-Hsin Chi, MD, Taiwan
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Oguz Coskun, MD, Germany
Tolga Coskun, MD, Germany
Long Cun, MD, China
Stephen E. Cyran, MD, USA
Sabine H. Dabritz, MD, Germany
Edward Darling, MS, CCP, USA
Kurt Dasse, PhD, USA
Christopher D. Derby, MD, USA
Pedro J. del Nido, MD, USA
Steven Deutsch, PhD, USA
Wen-Xiang Ding, MD, China
Anne Dipchand, MD, Canada
Thorsten Drews, MD, Germany
Brian Duncan, MD, USA
Yves Durandy, MD, France
Martin Elliott, MD, UK
Christina Feldmann, PhD, Germany
Francis Fynn-Thompson, MD, USA
Mark Gartner, MS, USA
Olivier Ghez, MD, United Kingdom
Carmen Giacomuzzi, CCP, USA
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Colleen Gruenwald, Canada
James M. Hammel, MD, USA
Mark Henderson, CCP, USA
Basil M. Henrick, LCCP, ECCP, Ireland
Roland Hetzer, MD, PhD, Germany
Edward Hickey, MD, UK
A. Craig Hillemeyer, MD, USA
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Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

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Hypothermia has been the mainstay for protection of the brain during cardiopulmonary bypass [CPB]. During cerebral ischemia, hypothermia slows consumption of high energy phosphate compounds, delays loss of ionic homeostasis and results in reduced amounts of free radical generation. These reductions in metabolic rates allow for reduced or absent CPB flow rates thereby facilitating improved surgical field conditions during complex operations in neonates. Hypothermic protection of the brain during periods of low or absent flow depends on the homogeneous cooling of all regions of the brain.

Some of the factors that may lead to nonhomogeneous or delayed brain cooling on CPB include length of cooling, temperature, blood pH management strategy hemodilution and systemic inflammatory response.

Results of the Boston Circulatory Arrest Trial, recent refinements in the conduct of deep hypothermic circulatory arrest and low-flow antegrade continuous cerebral perfusion as well as new innovative cerebral protection and monitoring strategies will be reviewed.
Endotoxin Preconditioning: Robust Brain Protection during Infant CPB through Genetic Re-programming

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Cardiac surgery involving periods of circulatory arrest is one of the only clinical circumstances in which a (controlled) severe global ischemic hit is administered to the brain in a premeditated fashion. CPB-related brain injury is therefore an ideal target for therapeutic pharmacological preconditioning.

Preconditioning is a concept whereby brief exposure to a stimulus provides robust protection – or tolerance – against the injurious effects of a subsequent more severe insult. Several different forms exist but the most exhaustively studied is acute preconditioning which provides brief protection over a few hours and seems to function at the post-transcriptional (protein) level. Delayed preconditioning instead occurs for far longer and is considerably more potent. Extremely low dose bacterial endotoxin (ET) is an example of a delayed preconditioning agent and can protect against cerebral ischemia by as much as 50%.

Recent efforts have been pursuing the clinical application of delayed preconditioning. This necessitates unravelling the signal transduction pathways involved. Rodent models have suggested that the process involves evolutionary historic pathways within the innate inflammatory response. Several generic signal-transduction pathways are involved, which explains the variety of delayed preconditioning agents known to work. In particular, the ancient Toll-like receptors are key initiators – one of which is activated by endotoxin.

Delayed preconditioning is fundamentally different from the previously popular acute form. New techniques such as microarray genome survey allow study of the activity of thousands of genes at any one time. Endotoxin preconditioning results in a large-scale reprogramming of the genetic response to injury. The result is a metabolic shut-down – akin to hibernation. Interestingly, the systemic inflammatory response is also refractory to activation.

Delayed preconditioning is therefore an attractive proposition for CPB-related tissue injury. In collaboration with one of the most prolific international teams studying preconditioning, we have been applying endotoxin preconditioning in a piglet model of neonatal brain injury following deep hypothermic circulatory arrest (DHCA). We have demonstrated the first successful application of delayed preconditioning in a higher mammal model of CPB-related injury.

Recent understanding of Toll-like receptors and their ligands has revealed other potential mediators of delayed preconditioning. Some of these are already in clinical use for other purposes and therefore represent potential agents for the clinical application of delayed preconditioning in clinical trials.
Circuit Miniaturization on the Systemic Inflammatory process in Neonatal CPB: The Experimental Findings

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Advances in perfusion strategies have played an important role in improving outcomes following repair of complex congenital heart defects. The influence of cooling strategy, temperature, duration of deep hypothermic circulatory arrest, and specific method of cerebral perfusion on neurologic morbidity have been extensively characterized. Similarly, the ability of pharmacologic agents to modulate the systemic post-cardiopulmonary bypass (CPB) inflammatory response has been previously elucidated in both the laboratory and clinical arena. However, modification of the extracorporeal circuit and priming components have received comparably less attention.

We recently showed that employment of a miniaturized circuit (priming volume 109 mL) and a bloodless prime was associated with a reduction in TNF\textalpha and neutrophil-priming capacity, decreased fluid sequestration and an improvement in both right ventricular function and pulmonary compliance following hypothermic low-flow perfusion in a neonatal piglet model. Furthermore, we showed that storage of blood products exacerbated the deleterious effect of the use of whole blood in the prime.

Follow-up studies in our laboratory demonstrated that our miniaturized circuit may also improve cerebral protection following both deep hypothermic circulatory arrest and hypothermic low-flow perfusion through abrogation of the cerebral no-reflow phenomenon.

This presentation, therefore, reviews current strategies utilized to minimize post-CPB systemic inflammation and highlights the empirical evidence from our laboratory demonstrating the beneficial role of a miniaturized extracorporeal circuit in this context.
Significant advances have been made in the technical performance of operations for infants and neonates with congenital heart disease. However, postoperative organ dysfunction is a frequent problem, particularly in hypoxic (cyanotic) infants and neonates. The infant heart is at high risk of damage from poor protection as a result of preoperative hypertrophy, cyanosis, and ischemia. Contrary to popular belief, these factors may make the immature (pediatric) heart more sensitive to cardioplegic arrest compared with the mature (adult) heart. We will describe the experimental infrastructure and subsequent successful clinical application of a comprehensive cardioplegic strategy that limits intraoperative injury and improves postoperative outcome in pediatric patients. The preoperative factors of cyanosis and pressure volume overload will be discussed followed by the strategies of warm cardioplegia with substrate enhancements, multi-dose cardioplegia, and a modified intergraded approach to allow ischemia only when visualization is needed in pediatric surgeries. The importance of using a blood cardioplegia solution specifically formulated for this use, as well the importance of monitoring the cardioplegia infusion pressure will also be discussed. A practical clinical framework based on these experimentally proven principles will then be presented to allow the surgeon to apply these strategies clinically. Application of these concepts should improve the safety of myocardial protection of the infant heart and reduce postoperative morbidity and mortality.
Assessment of Mortality Rates

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Payers, providers, and patients and their families are increasingly using health care outcomes in evaluation and choice of medical treatment. While adult cardiac surgery has been the focus of much research and discussion regarding what constitutes quality care and acceptable outcomes, the definition of quality and the benchmarks for outcomes in congenital cardiac surgery remain nebulous. However, if the field is to continue to progress, such standards of care must be developed.

Assessment of mortality rates in congenital cardiac surgery is more complex than in adult cardiac surgery due to the much wider range of procedures performed and the low frequency at which each individual procedure is performed. The Risk Adjustment for Congenital Heart Surgery (RACHS-1) method was created to allow a refined understanding of differences in mortality among patients undergoing congenital heart surgery while the Aristotle Basic Complexity Score was developed for measuring surgical performance. Multiinstitutional mortality rates for congenital heart surgery, derived from 1994-1996 data and reported in the original RACHS-1 manuscript (Jenkins KJ et al., 2002), continue to be used by centers as benchmarks for comparing their own results, both internally for quality improvement, and externally for patient education and advertising. However, these mortality rates may not represent standards to be attained in current practice since 1) much has changed in congenital cardiac surgery over the past 10 years leading to improved outcomes, and 2) they were obtained from a wide range of hospitals performing congenital heart surgery, not only centers with a specific commitment to treating children with congenital heart disease. More recent investigation has shown lower mortality rates at high quality pediatric cardiac programs despite a change in case mix with a shift away from low complexity operations.

The introduction of public reporting and pay for performance initiatives has invigorated debates about the relative benefits of administrative and clinical databases for comparing hospital and surgeon level mortality rates and the utility of hospital surgical volume as a measure of quality. There is much discussion regarding what constitutes good performance and how such information should be used for policy and payment decision making and public reporting. Knowledge of these issues is crucial both for evaluating and improving our own outcomes and for understanding how others are assessing our performance.

This presentation will summarize the various risk adjustment methodologies that have been created for assessment of congenital cardiac surgery mortality rates. The benefits and limitations of administrative and clinical databases for evaluating performance will also be reviewed. Currently available mortality standards will be discussed as well.
Precise measurement of cardiac output following stage 1 palliation of HLHS has previously been clinically unattainable. Postoperative management strategies have therefore been based on data that has been derived, by necessity, from assumptions. Mass spectroscopy allows for measurement of oxygen consumption. The combination of measured oxygen consumption (MVO2) and measured appropriate saturations can be applied to the Fick equation which then yields total cardiac output. Calculations of SVR, PVR (including the shunt in the circulation), oxygen delivery, and oxygen extraction ratio can be achieved. Rather than just a Qp:Qs ratio, associated indexed outputs allow for rational and appropriate respective vascular bed manipulation strategies.

**Findings:**
The overriding finding is that of extreme variability in primarily Qs. Qp is more stable. Manipulation of Qp:Qs is best performed by manipulating the Qs side of the equation via taking steps to diminish SVR. Alpha blockade and additional inspired CO2 are both effective means of systemic vasodilation and each demonstrated little effect on Qp.

Oxygen consumption is initially quite high but diminishes in the 1st 12 hours – likely as a consequence of recovery from cardiopulmonary bypass. Manipulation of MVO2 needs to be explored.

We compared measured CO data to that implied by SVC saturation, arteriovenous oxygen saturation difference, and omega (oxygen excess factor). A significant correlation was present but it was only weak to moderate in strength. There was however a very tight correlation with oxygen extraction ratio. On an absolute basis, these reflectors of cardiac output only loosely correlated with actual cardiac output because there is a lack of discrimination ability between oxygen consumption and delivery.

Below are examples of individual variations seen in SVR, PVR and other parameters. Note the broad individual variations.
Systemic inflammation is the nonspecific physiological response to a large variety of stimuli comprising contact between blood components of an individual and foreign surfaces and ischemia and reperfusion injury related to cardiac surgery. In neonates and infants, the systemic inflammatory response includes early complement activation, blood cell stimulation and induction of pro-inflammatory and stress proteins. The nuclear factor kappa-B and p38 mitogen activated kinase pathways are probably of central importance for the transcription of most inflammatory proteins that are up-regulated during and after cardiac surgery. Pro-inflammatory cytokines such as tumor necrosis factor-α (TNF-α), interleukin (IL)-1, IL-6 and IL-8 belong to this group. They have biological properties that relate to the stimulation of leukocytes, endothelial cells and virtually all parenchymatous cells, causing them to produce other inflammatory mediators, cytotoxicity and initiation of cell death. Normally, the inflammatory response is limited by a natural anti-inflammatory reaction that is mediated by anti-inflammatory proteins such as IL-10. Anti-inflammatory cytokines inhibit the synthesis of pro-inflammatory cytokines. By activating the hypothalamo-pituitary-adrenal axis, they stimulate cortisol release and hereby stop the systemic inflammatory response. In case of dysbalance between the pro- and anti-inflammatory response to cardiac surgery and uncontrolled inflammation, a systemic inflammatory response syndrome (SIRS) occurs that is characterized by fever and dysfunction of several organ systems. In general, there is a relation between the importance of the systemic inflammation and the occurrence of postoperative complications in neonates and infants.

The potential for the inflammatory response is probably multifactorial. Factors influencing this potential are as follows: 1) genetic predisposition due to the presence of different polymorphisms for pro- and anti-inflammatory cytokines, 2) gender, as female sexual hormones could modify the anti-inflammatory response, 3) preoperative conditions such as heart failure and/or hypoxaemia which lead to systemic and intramyocardial inflammation, and 4) drug treatments such as corticosteroids, phosphodiesterase inhibitors or β-agonists, which might shift the cytokine balance toward a net anti-inflammatory cytokine production.

There is, as yet, no specific treatment of the uncontrolled systemic inflammatory response syndrome. However, a modulation of this response can be achieved by pharmacological and technical strategies of the perioperative management. These strategies are aimed to enhance the balance in favour of the anti-inflammatory response to cardiac surgery by either decreasing the production of pro-inflammatory mediators or removing them from the circulation, or by enhancing the production of the anti-inflammatory mediators.
Past, Present, and Future of Pediatric Cardiac Surgery in a Developing Country: The Turkish Experience

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Pediatric cardiac surgery was first introduced to Turkey in the early 1960s. Dr. Aydin Aytaç, who had general surgery training at St. Francis Hospital in Wichita, Kansas, and cardiac surgery training at Emory University in Atlanta, Georgia, will discuss the early days of pediatric cardiac surgery in Turkey, its key figures and some of the professional accomplishments of him and his colleagues. Many of the “first-time” cases in Turkish medical history were performed by Dr. Aytaç, such as the first successful open heart surgery in Turkey with a heart-lung machine (1962), a total correction for TOF (1963), congenital aort stenoz (1964), direct communication of right pulmonary artery with left atrium (1965), Mustard operation for TGA (1970), Aorta-Pulmoner Septal Defect (1970), Double Outlet Rt. Ventricul (1972), Pediatric atrial Myzome (1973), Complete A-V Canal Defect (1977), and Senning operation TGA (1983). Dr. Aytaç also performed the world’s first aorta-right ventricular tunnel operation in October 1972. Open heart surgery on a one-day old baby with pulmonary atrezi was performed in 1992. In 1995, Drs. Aytaç and Turkoglu and in 2002 Drs. Aytaç and Akcevin performed operations for TOF without the right pulmonary artery. Operations on TOF without left pulmonary artery were performed in 1997, 1998 and 2004 by Drs. Aytaç, Turkoglu, and Alkan.

Dr. Aytaç was the founder and chairman of the first pediatric cardiac surgery department in Turkey and doctors who had their residency with him performed many “first-time” pediatric cardiac surgeries, including neonatal aort D (Dr. Ikizler, 1979), Fontan operation (Dr. Ikizler, 1980), pulmoner konduct (Dr. Ikizler, 1985), arteriel switch (Dr. Sarioglu, 1990), Corno operation (Dr. Sarioglu, 1992), Ross operation (Dr. Oto, 1998), Ross-Konno (Dr. Sarioglu, 1999) and multiple valve pulmoner conduit (Dr. Aslamaci and team, 1999-2000).

Dr. Aytaç will discuss the current state of pediatric cardiac surgery. Concluding remarks are optimistic regarding the future, as the country can now claim many highly qualified pediatric cardiac surgeons and state-of-the art surgical facilities.
Routine Ventricular Assist Following Norwood Procedure

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Conventional postoperative management after the Norwood procedure in patients with hypoplastic left heart syndrome (HLHS) suffers from three main shortfalls. First, the early postoperative care is often labor-intensive, and ironically (despite sometimes heroic efforts), when babies die, health care providers often feel like failures and in the worst scenarios, surgeons or other physicians create cultures of blame. Secondly, hospital survival is inconsistent in many centers especially the ones with small surgical volume and limited experience. Thirdly, survivors often show evidence of significant neurological impairment.

Recent enthusiasm for an alternate source of pulmonary blood flow utilizing an RV-PA conduit as opposed to an aortopulmonary shunt has helped many of these low (and some high) volume centers achieve improved stage I survival. However, the RV-PA conduit serves no advantage by the time infants get to stage II (Glenn) and it may be a disadvantage with respect to long-term right (systemic) ventricular function, neurological outcome and even an increased mortality rate at the time of Glenn.

Beginning in January 2001, we adopted the strategy of routinely placing all our patients with HLHS on mechanical ventricular assist support immediately after their Norwood procedure. This decision was driven by recognition of the HLHS shortfalls described above and by substantial laboratory research defining the beneficial effects of increased cardiac output following exposure to commonly employed CPB strategies (such as deep hypothermic circulatory arrest—DHCA—or continuous low flow CPB) particularly when there is post-CPB hypoxemia. No attempt was made to balance the systemic and pulmonary circulation. Since an oxygenator was not used in the circuit, a much lower level of anticoagulation was utilized. Once the lactate level normalized, the amount of VAD support was weaned.

Forty-two consecutive infants have been managed with this strategy. The average time of VAD support was 2.3 days and most our recent patients are removed from VAD between 24-36 hours postoperatively. The overall hospital survival has been 37/42 (88%). Cerebral oxygen saturations have generally been maintained above 50% and outcome data, which are now available for 23 patients, demonstrate outstanding neurologic outcomes at short and intermediate term follow-up.

Routine postoperative use of VAD can support the increased cardiac output demands of infants following Norwood procedure and results in a stable postoperative convalescence. This strategy can simplify postoperative management, lead to excellent hospital survival, and possibly augment cerebral oxygen delivery resulting in improved neurological outcomes for these patients.
Pediatric Mechanical Circulatory Support in Japan and Development of Tiny Rotary Blood Pump

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Recent development of surgical treatment to even the most complex cardiac anomalies in neonates, small infants and children has led to an expanded role for mechanical circulatory support for post cardiotomy failure. Also an increasing population of adolescents with Fontan procedure will ultimately develop circulatory failure and may be candidates for long term implantable circulatory support system or heart transplantation. However, the pediatric population have not attained the same level of technological development as we have seen for the adult population. The use of mechanical assistance as a bridge to transplantation or a bridge to recovery are the main indications for mechanical circulatory support in neonates, infants and children. The problems of Japan are the organ donor shortage and also a limited heart transplantations only adult. These situation has led us to develop a new tiny rotary blood pump (TinyPump) with the super-low priming volume of 5 ml.

We review our experience of mechanical circulatory support in Japan and development of TinyPump.
Pediatric Mechanical Circulatory Support in Europe

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Mechanical support of the failing myocardium has become standard therapy for adults who fail medical management. Several device options are available for adults in most clinically relevant indications including bridge to transplantation, bridge to myocardial recovery or destination therapy. Historically, these same options have been unavailable for children. The main cause for limited device availability for pediatric circulatory support is clear—the small number of affected children makes it difficult for manufacturers to justify the expense and other resources required for the limited pediatric market. Extracorporeal membrane oxygenation (ECMO) and centrifugal pump based ventricular assist devices (VADs) remain the most commonly employed circulatory support modalities for pediatrics; however, neither ECMO nor older centrifugal pump based VADs are implantable and, for the vast majority of cases, are suitable for support of only a few weeks duration. The need for improved VAD technology for children is widely recognized as a major unaddressed area in pediatric cardiology and cardiac surgery.

During the last few years, substantial advances in pediatric circulatory support have been made suggesting the outlook for this field is brighter. In the spring of 2004, the DeBakey VAD Child (MicroMed Technology, Inc., Houston, TX) was granted Humanitarian Device Exemption (HDE) status by the Food and Drug Administration for use in children. This device has been used successfully to provide temporary left ventricular support as a bridge to cardiac transplantation for children from 5–16 years of age with a BSA > 0.7 m$^2$ and < 1.5 m$^2$ and is fully implantable in this size range. The Berlin Heart VAD (Berlin Heart AG, Berlin, Germany) is a paracorporeal system that employs pneumatically driven, thin membrane pumps to provide pulsatile flow. The Berlin Heart VAD is available in a variety of pump sizes (10-80 ml) and is capable of providing support for the entire size range of pediatric patients including neonates. The worldwide experience with the Berlin Heart VAD in pediatric patients now exceeds one hundred patients. In the United States, despite device availability only on an emergency basis, more than 30 cases have been performed; attempts to obtain HDE status for the Berlin Heart VAD are currently underway. The Pediatric Circulatory Support Program from the National Heart, Lung and Blood Institute (NHLBI) of the National Institutes of Health was established to support early stage development of novel pediatric circulatory support devices. In the spring of 2004, five contracts were awarded by the NHLBI to support preclinical development for a range of pediatric VADs and similar circulatory support systems. The support of early development efforts provided by this program will hopefully yield several devices that are clinically useful within the next five years.
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

**Emergency Use of Pediatric Circulatory Support**

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Acute cardiovascular collapse in pediatric patients with congenital heart disease carries a dismal prognosis with an estimated survival of 14 to 41%. The use of extracorporeal membrane oxygenation (ECMO) in the high risk patient population has been applied since initial reports in the 1970’s. Reports from Duncan, et al., have shown that pediatric patients with heart disease requiring ECMO for cardiac assist have a similar survival when compared with those requiring ECMO for all other indications. Furthermore, rapid deployment ECMO can be used safely and effectively in pediatric patients.

We recently reviewed our experience with 27 patients undergoing veno-arterial (VA) ECMO at a median age of 27 days. There were 16 survivors (59%). Interestingly seven of eight patients with cardiomyopathy (88%) survived and seven of 12 single ventricle patients survived. Fifteen patients (56%) were undergoing cardiopulmonary resuscitation at the time of ECMO. Of these, 73% survived.

Our results and those of others suggest that resuscitation ECMO is an appropriate application of VA ECMO in pediatric patients with cardiac disease. It appears that single ventricle patients experiencing sudden cardiopulmonary collapse and cardiomyopathy patients have favorable outcomes. Patients less likely to improve are those failing to wean from bypass and postoperative ventricular failure.

Management of Pediatric Patients after VAD Implantation

Stiller B
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Up to 02/2006, Berlin Heart EXCOR systems have been used for circulatory support in 73 infants and children aged up to 18 (mean age 7.5) years with severe circulatory failure resistant to pharmacological therapy at our institution. These were patients suffering from cardiomyopathy, fulminant myocarditis, end-stage congenital cardiac defects and acute heart failure following congenital heart surgery. Mean EXCOR support time was 36 days (range 0-420 days). Forty-three patients (60%) survived up to transplantation or after weaning and 37 (51%) of them, including 8 infants, were discharged home. One infant is still on VAD support. These results in patients with very advanced disease have improved significantly during the past few years due to technical developments and growing experience in the treatment of patients on the device and in postoperative care. In the management of children after EXCOR implantation we apply the following strategy:

When a bi-ventricular EXCOR device (BVAD) has been implanted, usually no inotropic medication is given. Changes in blood pressure are managed via:
1. Changes of pump parameters (interval of systole or diastole, pump rate)
2. Volume infusion (volume ↑) or diuretics (volume ↓)
(We give noradrenaline only in the case of peripheral resistance loss.)

When a left ventricular EXCOR device (LVAD) has been implanted, the RV should be closely monitored by echocardiography for RV diameter and TV regurgitation. Central venous pressure must be maintained in low-normal range. Otherwise, for RV support we give: diuretics, milrinone, catecholamines, nitric oxide, ilomedin, sildenafil, etc.

If pharmacological support is not successful there is a need for a BVAD. In cases of good unloading of the left ventricle by LVAD the afterload reduction of the right ventricle tends to result in rapid improvement of right ventricular function.

Enteral nutrition is started just a few hours after VAD implantation. Extubation and mobilisation should be performed as early as possible. The children are able to walk around while on the device, and we have never seen dislocation of a cannula or a technical defect of the system.

When there are signs of myocardial improvement and weaning seems achievable we add beta blockers and ACE inhibitors and reduce the pump rate (with a pump stop under additional safety precautions) to check by echocardiography whether native ventricular function is adequate.

Our weaning and anticoagulation protocols will be presented at the meeting.
For over two decades ECMO has been standard practice of temporary support for cardiac and/or respiratory failure. For patients with isolated respiratory failure, venovenous support is sufficient. Double lumen catheters placed into the right atrium via the internal jugular vein can provide adequate support for children up to 12 kg. For larger children, it is necessary to establish venous drainage and return from separate large caliber vessels (usually drainage from the femoral vein and return through the internal jugular vein). Patients with cardiac or cardiorespiratory failure require support with both gas exchange and hemodynamics. Therefore, venoarterial access is required. For post cardiotomy patients with cardiac failure, cannulation directly of the aorta and right atrium via an open sternum is the most expeditious option. However, in children where long term support is anticipated, cannulation of the internal jugular vein and common carotid artery is preferred due to decreased infectious complications. For patients who are not post cardiotomy, venoarterial access in small children (<20 kg) is obtained via the internal jugular vein and common carotid artery requiring a cervical cutdown. In larger children, access via the femoral artery and vein is possible and can often be performed percutaneously. For patients with cardiac failure and loss of ventricular contractility, adequate egress of blood from the left ventricle needs to be established early with either direct cannulation of the left atrium, placement of a percutaneous left atrial drain, or an atrial septostomy.

At the University of Michigan, we currently are utilizing a roller pump for long term support with a centrifugal pump reserved for ECMO transports and emergency circuits. The Medtronic Kolobow Spiral Coil Membrane Lung is the only membrane lung suitable for long-term support in the United States. Due to the long prime time for this oxygenator, we utilize a hollow fiber oxygenator for the ECMO circuits needed in an emergent situation with exchange of the oxygenator when plasma leakage occurs. Many heparin bonded circuits and oxygenators or currently under investigation, but are not in routine use in our institution at this time.

The management of patients with respiratory failure is directed at minimizing V/Q mismatch, optimizing fluid status, maximizing hematocrit, reducing metabolic needs, and treating the underlying cause (bacterial, viral, autoimmune, ARDS). Post cardiotomy ventricular failure often will respond to 24-72 hours of support. If not, residual cardiac defects that require surgical correction must be identified and corrected. Pulmonary hypertension can be improved with inhaled nitric oxide. In patients with newly diagnosed cardiomyopathies, the cause should be identified and treated aggressively if possible. End stage cardiac failure can be supported temporarily, but listing for transplant or conversion to a long term ventricular assist device must be discussed early.
ECMO is the best, if not the only, method for mechanical life support for acute cardiac failure in children. The reason is that acute cardiac failure is usually biventricular and often involves respiratory failure at the same time, therefore ventricular assist devices, however small, do not provide total support. Indications are cardiac failure unresponsive to pharmacologic treatment. The most frequent cause is postoperative cardiac failure during or following cardiac operations, but ECLS is also used for cardiomyopathies, preoperative evaluation, and cardiac arrest of unknown cause to permit time for diagnosis and treatment. Venoarterial access is always required, either directly into the right atrium and aorta (in children whose chest is already open) or via the neck vessels in smaller children or femoral vessels in larger adolescents. Eighty percent of the venous return is routed through the extracorporeal system so that only 20% goes through the heart and lungs. There is a risk of clotting particularly in the left atrium and left ventricle. If the left ventricle does not empty through the aortic valve then an atrial septostomy or left atrial drain must be created to avoid left ventricular over distension. Post-cardiotomy failure is usually of limited duration and will improve within 24-72 hours allowing ECMO support to be weaned and terminated. When function does not recover, attempts to identify residual cardiac defects should be instituted with early repair when possible. If no surgically correctable causes can be identified, a decision should be made early as to whether the patient is a candidate for cardiac transplantation and/or a long term ventricular assist device. If so, the call should be put out for donors immediately. If not, a time limit should be established to determine reversibility of the cardiac failure (typically 1 to 2 weeks).
ABCs of ECMO in Pediatric Patients: Respiratory Support

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The Extracorporeal Life Support registry reports 24,133 patients treated with extracorporeal life support (ECLS). Eighty-three percent of those patients are placed on ECLS for respiratory support, with the remained placed on for cardiac support. Of the neonatal respiratory patients, 76% survives to discharge, while only 56-52% the pediatric and adult patients with respiratory failure survive to discharge. The large difference is thought to be related to the differing underlying disease processes between the neonate and pediatric patient. The major diseases treated in the newborn period are meconium aspiration syndrome, persistent pulmonary hypertension, congenital diaphragmatic hernia, sepsis/pneumonia, and larger babies with respiratory distress syndrome. Older patients may have pneumonia, bacterial or viral, aspiration, ARDS from any cause. ECLS or extracorporeal membrane oxygenation (ECMO) is usually initiated after other forms of conventional therapy have failed. There are two forms of ECMO, venoarterial (VA) using the carotid artery and jugular vein, and venovenous (VV), using either a double lumen catheter placed in the jugular vein, or two venous catheters, usually placed in the jugular and femoral veins. A typical ECMO run for respiratory failure in the newborn is 6-8 days, while in the older child and adult, as long as 3-4 weeks may be required before full recovery occurs. Complications include bleeding, with intracranial hemorrhage the major cause of death in the newborn ECMO population, hypertension, emboli either clots or air, mechanical failure. Typically a roller occlusion pump with a silicone membrane lung are used in the United States for routine ECMO. For specialty uses such as rapid deployment circuits, the centrifugal pump and microporous hollow fiber membrane may be used. Each system has their positive and negative factors. Equipment and catheters used will be discussed. In summary, a complete understanding of prolonged extracorporeal technology is needed before initiation of this therapy or program. Coagulation methods are key for a successful run. The number of patients is usually relatively small annually (average 12 per ECMO Center), so continued emergency training and competency review is key for any successful EDCMO program.
Automatic Suction Control in Pediatric ECMO

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Background:
We organised the set-up of our ECMO with a rotary blood pump and automatic suction control. We try to achieve this ease of working as well in our new pediatric configuration.

Patients:
From 1996 through 2005, 137 ECMO runs were performed in 131 patients. Median age was 34,5 years (0 - 79,5 years). Main indications were non-neonatal respiratory failure (n=71), neonatal respiratory failure (n=10) and Cardiac failure (n=50). Median time on ECMO was 5 days (0 - 21d). All patients had a biopump with automatic suction control (servoregulator), allowing to run the system without continuous surveillance. The target inflow pressure was set at -40mmHg.

Results:
Long ECMO runs proved possible with inflow pressures as low as -60mmHg in without the creation of hemolysis. The occurrence of hemolysis (free plasma hemoglobin) indicated the formation of thrombus in the biopump or other parts of the circuit. Based on this experience we implemented a new pediatric set-up with smaller priming volume and automatic suction control incorporated in the pump console. The Medos DP2 pump head (priming volume of 17cc) was used in 5 cases with automatic suction control.
Pump flow and ECMO performance were similar to the biopump. Visual control for cloth formation in the pump head is however less obvious.

Conclusion:
Automatic suction control with servoregulator is safe and allows a standardized management of ECMO. It is possible in neonates and can be performed with the miniaturized Medos DP2 circuit.
Clinical Outcomes and Experience of 12 Children Managed Extracorporeal Membrane Oxygenation in Fuwai Hospital

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Abstract Background:
Extracorporeal membrane oxygenation (ECMO) has been used in pediatrics for a long time. Increasingly complex repairs in neonates and infants with complicated congenital heart disease have lead to ECMO increase in cardiac failure

Objectives:
Retrospectively summarized and analysed the files of consecutive 12 pediatric ECMO performed in Fuwai Cardiovascular Hospital.

Materials and Methods:
We reviewed the clinical protocols of 12 pediatric ECMO before and after cardiac surgery from Nov. 2004 to Nov. 2005 in our hospital. ECMO equipments of Medtronic Ltd were utilized to every patient and the inter-surface of the system is covered completely by heparin-coating technique. All patients applied veno-artery ECMO and active clotting time (ACT) maintained between 146 – 258sec and heparin usage dose was 5 – 20U/Kg/h. Mean blood flow was 40 – 220ml/Kg/min during ECMO assistant period.

Results:
The shortest ECMO time was 55hrs and longest was 266hrs and mean time was 120hrs. ECMO were weaned off successfully in 9 patients (75%) and 6 of them (67%) were survival to discharged and 3 of them were died of post-operation complications. 3 patients could not been weaned off ECMO. Total survival discharge rate was 50%(6/12) in this cohort study. Lactic acid concentration of artery blood before ECMO in survived patients was significantly lower than that of dead patients (p=0.022). Weights between survival and dead also had statistic difference (p=0.019).

Conclusions:
ECMO is an effective mechanical assistant therapy method for cardiac and pulmonary failure after cardiac surgery in pediatric complicated congenital heart disease and ECMO can been used as bridge for heart transplantation to those severe end-stage heart disorder in children. Perfect correction of abnormality and earlier usage of ECMO for heart lung failure patient and avoiding the main organs from un-recovery trauma are still the key point of success of ECMO.

Key words: ECMO, cardiac surgery, pediatrics, congenital heart disease
Experience with Pediatric LVAD Support

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Introduction:
We report on our experience with pediatric left ventricular assist devices (LVAD) as a bridge to heart transplantation in infants and small children.

Methods:
Since 1993, 7 out of 192 VAD patients were infants or small children with an age ranging from 9 months to 7 years. Underlying heart diseases were dilative cardiomyopathy (n = 3), fibroendocardial elastosis (n=2), and Ebstein’s malformation (n = 1), as well as congenital valve disease (n=1). One patient had undergone implantation of an extracorporeal membrane oxygenation system before. Systems used were Medos and BerlinHeart Excor.

Results:
In 6 cases, a left ventricular assist device (LVAD) implanted, whereas 1 patient required right ventricular support. Five Patients underwent heart transplantation, one died during support. The support interval ranged from 14 to 145 days (mean 70 days). Severe complications were only seen during the early experience, i.e. with the Medos system. With an improved perioperative management protocol all (BerlinHeart) patients remained free of complications (no bleeding, no right heart failure, no infection, one TIA).

Conclusions:
Pediatric LVAD support with pneumatically driven systems is feasible with a low risk and excellent outcome.
Utilization of the Berlin Heart as a Bridge to Transplantation in Pediatric Patients

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Until recently centrifugal and roller pumps, as part of an extracorporeal membrane oxygenation circuit, have been the mainstay of mechanical bridge to transplantation in the pediatric population. We present our experience over the past one year with the Berlin Heart as a bridge to heart transplantation. Four patients aged 6 months to 9 years were implanted. Patient weight ranged from 9.0 to 40 kg with a body surface area from 0.27 to 1.04 kg/m². The indication for each was severe heart failure secondary to cardiomyopathy. One patient also had a cardiac tumor. Ten and 25 ml pumps were utilized. All patients received only LVADs. There were no significant complications of implantation and the average time to extubation was 4 days. All patients resumed a regular diet. Hemodynamic support was satisfactory in each of the patients with an average pump index of 3.2 L/m². No drive line infections were observed, two patients were treated for other nosocomial infections. Anticoagulation was managed predominately with continuous heparin infusion with clopidrogel, aspirin and dipyridamole added to some patients’ treatment regimen.

Prothrombin time, partial thromboplastin time, platelet activation and thrombelastograms were followed in these patients. One patient required three pump changes for thrombus formation. Thrombus was noted in the other three pumps as well. No conclusive correlation was observed between any of the laboratory measurements and thrombus formation. Two of these patients experienced cerebral infarcts. The duration of support was 8 - 40 days with a mean of 20.5 days. All patients were successfully transplanted and discharged to home. Both patients with neurologic insults have recovered. In conclusion, we have utilized the Berlin Heart to successfully bridge four pediatric patients to transplantation over the past year. We have observed a decrease in the acuity of care and increase in the ability to interact with family during the bridge time period when compared to ECMO. There was a minimal incidence of infection. Management of anticoagulation in these patients has proved challenging and resulted in thrombus formation and stroke.
Sub Cutaneous Low Molecular Weight Heparin for Management of Anticoagulation In Infants on Excor Ventricular Assist Device

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Introduction:
Anticoagulation in infants and children on a ventricular assist device presents particular challenges; unfractionated heparin has poor bioavailability, it can be difficult to achieve a stable anticoagulant effect and in the long-term there is a risk of osteopenia. Long-term warfarin can be difficult to manage in infants on formula milk due to vitamin K supplementation of these milks. We review our recent experience with subcutaneous low molecular weight heparin (LMWH).

Methods:
Since 1/11/05, 2 patients received a left ventricular assist device (Excor, Berlin Heart) as a bridge to transplantation. Initial anticoagulation consisted of unfractioned heparin infusion (UFH) beginning 6 hours after implantation to maintain an APTT of 70 seconds, checked every 4-6 hours. Platelets count (aim > 80 000/ml) and thromboelastogram traces were assessed daily. Antithrombin III required substitution at least 3 times weekly to maintain levels>70 iu/dl. Due to the unpredictable anticoagulant effect of UFH both infants were switched to sub-cutaneous LMWH 100u/kg/dose twice daily aiming for an anti-Xa activity between 0.5 and 1.0 IU/ml, evaluated every 1-2 days. Aspirin was added on day 4 (1 mg/kg/day) checking platelet aggregation every 2-4 days aiming at arachidonic acid stimulated aggregation 10-30 % of baseline, collagen 100% of baseline. Dipyridamole (4mg/kg) was added once stability was reached if platelets count exceeded 150 000/ml.

Results:
There were no clinical thromboembolic or bleeding events. LMWH requirements and anti-Xa activity are given in table. No Antithrombin III substitution was necessary on LMWH. One patient was successfully transplanted; the second patient is still awaiting transplantation.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age at Excor implantation (days)</th>
<th>Weight (kg)</th>
<th>Time on Excor (days)</th>
<th>Outcome</th>
<th>LMWH (IU/kg/inj) min-max</th>
<th>Anti Xa (IU/ml) min.</th>
<th>Anti Xa (IU/ml) max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>425</td>
<td>8.2</td>
<td>27</td>
<td>Transplanted</td>
<td>100-200</td>
<td>0.19</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>275</td>
<td>10</td>
<td>26</td>
<td>Excor</td>
<td>100-200</td>
<td>0.23</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Conclusions: Using an multisystem approach to anticoagulation, it was possible to use LMWH for the duration of support awaiting for transplantation in these 2 patients.
Complex Transport of a Hurricane Katrina Evacuee on BiVAD Support

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Background
In many U.S. hospitals, providing mechanical circulatory support (MCS) is routine, and the systems in place to sustain these efforts are taken for granted. Hurricane Katrina challenged the durability of these systems in three pediatric hospitals. A 15-year-old boy with dilated cardiomyopathy (DCM) who was receiving biventricular MCS at a New Orleans hospital was successfully transported by Angel One Transport from Arkansas Children’s Hospital across state lines to Texas Children’s Hospital (TCH) where he was stabilized and received an orthotopic heart transplant.

Case Report
The patient was receiving MCS, as a bridge to cardiac transplantation, via paracorporeal biventricular Thoratec® iVADs for over seven months at Tulane University Hospital in New Orleans. Hurricane Katrina made landfall on August 29, 2005 necessitating the evacuation of the patient. Three different institutions coordinated the transport of the patient to a pediatric facility with an active MCS and heart transplant program. The transport was complicated by a depleting electrical supply, moving a 400 lb. drive unit down multiple flights of stairs, and several instances of hand-pumping the iVADs. At TCH, the patient was evaluated and stabilized. The social work and child life staff provided significant emotional and psychological support. After 260 days of MCS, a donor heart became available, and an orthotopic heart transplant was performed.

The patient’s iVAD cannulae had been precariously placed, and thus to facilitate a hazardous dissection during explant and to avoid the need for femoral cannulation, the previously placed cannulae were used to initiate cardiopulmonary bypass prior to skin incision. This reduced the risk of bleeding and air embolism. The child recovered and was discharged from the hospital on postoperative day #31.

With coordinated care, complex patients on MCS can be safely transported between centers. Establishing cardiopulmonary bypass with direct cannulation of the iVADs can facilitate reoperative sternotomy.

*corresponding author
Introduction:
Herein we report our experience with left VAD with centrifugal pump in five pediatric cases, less than 15kg, with postcardiotomy heart failure.

Materials and Methods:
Between March 1, 2004, and July 1, 2005, five patients, 4 months to 4 years (1.78±1.65years) and 6 to 14.5kg (8.98±3.57kg), were affected with postcardiotomy hemodynamic failure and treated with left VAD was used in all cases. The patients were 1. multiple VSD, mitral valve stenosis and regurgitation, tricuspid stenosis, and right coronary valve collapse, pulmonary hypertension; 2. VSD, ASD, and arch hypoplasia; 3. pulmonary atresia and VSD, extra-conduit Fontan procedure; 4. LCAPA and bicuspid regurgitation; 5. TOF and CAVC. One case began VAD because failure to wean off CPB and others were set up VAD postoperative 19 to 51 hours (36±15.89hours). All patients were drained from left atrium and four of arterial cannula was placed in ascending aorta, one put in left femoral artery. The flow rate were maintained 70-100ml/kg.min (about 1.5-2.0L/m².min). All patients were treated with peritoneal dialysis because of oliguresis or anuresis before or during VAD support.

Results:
After VAD support, all cases showed improved hemodynamic and decreased inotropic such as adrenalin except case 4, because of progressive right ventricular failure. Two cases, case 1 and case 5, were successfully weaned off the VAD at 40 and 74 hours supports and discharged without obvious complications. Other three cases were died from neurological complication (case 2), bleeding (case 3), and right ventricular dysfunction (case 4).

Conclusion:
VAD appears to be one of the choices as a bridge to postcardiotomy recovery even in the infant and small children. The choice of the device should be decided according to the right ventricular function, lung function. Complications such as bleeding, infection and thrombolitics are not uncommon and should be treated conservatively.
Mechanical Heart Valve Performance in a Pulsatile Pediatric Ventricular Assist Device

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Background
A pulsatile pediatric ventricular assist device (PVAD) is currently under development at the Pennsylvania State University. The dynamic stroke volume of this PVAD is approximately 12 mL. Two types of mechanical heart valves were examined in this study: a size 17 monoleaflet valve (Björk-Shiley Monostrut) and a size 16 bileaflet valve (CPHV, CarboMedics Prosthetic Heart Valve). The same size and type of valve was used in the inlet and outlet positions of the PVAD.

Materials and Methods
In vitro testing was performed on a mock circulatory loop that simulated systemic capacitance and resistance. A high speed video and data acquisition system was used to simultaneously record video images and pressure and flow waveforms for the Monostrut valve and the CPHV for an array of test conditions that varied heart rate and systolic duration. These recordings were then used to characterize and compare the hydrodynamic and dynamic performance of the two types of mechanical heart valves at identical operating conditions.

Results
Testing over a range of operating conditions showed that the hydrodynamic and dynamic performance of the Monostrut valve was more sensitive to changes in heart rate and systolic duration than the CPHV. The CPHV had higher regurgitant volumes and peak regurgitant flows than the Monostrut valve in both the inlet and outlet positions at all operating conditions. The stroke volume for the CPHV was higher than the stroke volume for the Monostrut valve for most operating conditions.

In the inlet position, the Monostrut valve had longer opening times than the CPHV. The CPHV took longer to close than the Monostrut valve for most operating conditions due to asynchronous closure of leaflets. The time that the valve was closed was shorter for the Monostrut valve than the CPHV. In the outlet position, the Monostrut valve took longer to close and was closed for shorter time than CPHV for most operating conditions.

Conclusions
These results show that the Monostrut valve and CPHV have different performance characteristics when tested at identical operating conditions. Additional testing is underway to identify the optimal operating conditions for each type of valve. Hemolysis and durability testing will also be completed prior to final valve selection.

Acknowledgements
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Heart Transplantation in Grown-up Congenital Heart Disease Patients


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Introduction:
End-stage Congenital Heart Disease (CHD) is an important indication for paediatric heart transplantation (HTx) as well as in adult population. An increasing number of grown-up congenital heart disease (GUCH) patients profits from advances in surgical techniques and management. The purpose of this retrospective analyse is to compare the survival rate of GUCH patients who underwent HTx versus adults without CHD. To find out, whether HTx is a considerable therapeutic option for grown-up pts. with pre-treated congenital heart diseases (CHD), data of 15 adult patients, who underwent Htx from 1989 until 2006 because of different CHD were retrospectively analysed and compared with the population of 1300 adult (> 16 years) transplant recipients with different other indications.

Results:
From 1989 until February 2006 15 GUCH pts. (8 male/7 female) were transplanted because of CHD. All patients were in NYHA IV. 10 patients have been pre operated, 5 patients twice. Mean age was 34,06±3,9 years. There were 5 cases of acute renal failure. 1 female pt. died 1.3 months postoperative because of intra cerebral infarction, 1 male pt died 4 years after HTx because of OKT 3 monoclonal antibody resistant rejection, 2 patients died because of multiple organ failure 4 days and 30 days after HTx respectively, 11 pts. are still alive. The Kaplan-Meier survival-rate is 73% vs. 80% in pts. with non-congenital indications in 1 year.

Conclusion:
HTx in GUCH can be performed without an increased risk and with a good long-term prognosis similar to adult patients without CHD. Previous palliative operations do not effect the good outcome.
Result of Pediatric Cardiac Transplantation with or without Bridge Methods

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Introduction:
Cardiac transplantation is a treatment for children with end-stage heart failure or complex inoperable congenital defects. Due to the shortage of pediatric donor hearts, various bridge methods have been used for pediatric recipients to prolong the waiting time. The purpose of this study was to evaluate the long-term outcome of bridge and non-bridge support after pediatric cardiac transplantation.

Methods:
From March 1995 through June 2004, 18 pediatric patients underwent cardiac transplantation. Six patients (33.3%) had received bridge methods either biological or mechanical methods before transplantation. Eight patients (44.4%) required extracorporeal membrane oxygenation (ECMO) support perioperatively. Data and charts of these patients were reviewed. We recorded the causes of death and analyzed the long term outcome.

Results:
Five of the ECMO group (62.5%) can be successfully decannulated and discharged home with excellent functional class. There were no differences in rejection rate, survival rate, and functional class of the bridge and non-bridge group. The overall one-year and five-year survival rate of these patients was 83.3% and all of them are in good functional class.

Conclusions:
Pediatric heart transplantation can be accomplished with excellent early survival despite multiple prior cardiac operations and relative severity of illness. For the various small sized pediatric patients, mechanical circulatory support using ECMO is suitable in the management of sudden collapse while waiting for heart transplantation or for graft dysfunction after cardiac transplantation. The mortality rate is acceptable in this very high risk group of patients and the long-term outcome is good.
Introductions: Acute myocarditis is usually a self-limited disease. However, some patients may experience a critical course, and they will have no chance to survive if no mechanical circulatory support is given in time. Acute respiratory distress syndrome (ARDS) in pediatric patients is also associated with high mortality rate. Clinical conditions still deteriorate in severe patients. In such circumstance, extracorporeal membrane oxygenation (ECMO) can provide a chance of survival.

Methods: From July 2000 through June 2005, there were 13 pediatric patients receiving emergency treatment of ECMO for cardiogenic shock (n=4) or severe respiratory failure (n=9) in our hospital. The median age was 4.3 years old (range: 0.1-19.1). For the group of fulminant myocarditis, cardiogenic shock persisted despite high doses of inotropic support. Venoarterial ECMO was used. For the group of ARDS, all the patients had AaDO2 more than 600 mmHg and/or persistent hypotension before ECMO setup. Initially, 4 patients underwent setup of venoarterial-ECMO and 2 patients underwent setup of venovenous-ECMO and the ECMO blood flow was 63-85 ml/Kg. The ECMO support was shifted to venovenous mode in one venoarterial-ECMO patient after hemodynamics were stabilized but respiratory function was still severely impaired.

Results: The ECMO survival rate for the myocarditis group was 75% and for the ARDS group was 50%. The median ECMO supporting time for the myocarditis group was 137 hours (range 72-159) and for the ARDS survivors was 99 hours (range 47-684). The survival rate of the ARDS patients with sepsis (75%) was not inferior to the ARDS patients without sepsis (40%).

For the myocarditis group, the culture data showed enterovirus type 71 for two cases, coxsackie virus for one case and none for one case. One patient passed away due to sepsis.

For the ARDS group, the cause of mortality was hypoxic encephalopathy in 1 patient and intra-cranial hemorrhage in another patient. The hypoxic encephalopathy was probably due to unstable hemodynamics before setup of venoarterial ECMO. The intra-cranial hemorrhage was the side effect of the systemic anticoagulation with heparin.

All the ECMO survived patients were discharged from the hospital. With regard to the complication in the survivors, one child had mild left hemiparesis probably due to prolonged ECMO use (684 hours). His neurologic function improved gradually and he can now run independently. One myocarditis patient surviving the ECMO had recurrent symptoms of congestive heart failure 2 months later. She passed away 3 months later while waiting for heart transplantation. All other survivors are in New York function class I.

<table>
<thead>
<tr>
<th>Group</th>
<th>Survival rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>myocarditis</td>
<td>75%</td>
</tr>
<tr>
<td>ARDS</td>
<td>56%</td>
</tr>
</tbody>
</table>
Conclusions:
There is no chance of survival without mechanical circulatory support for the patients with acute fulminant myocarditis and circulatory collapse. It was usually reported in the literature that a high success rate could be achieved for the application of ECMO to the patients with acute fulminant myocarditis. However, if the pathogens attack other organs such as the brain, the patients still have risk of death. Heart conditions such as rhythm and contractility still have the chance to deteriorate again, so close follow up for these patients is necessary. ECMO can rescue more patients with severe ARDS, even in the condition of septic shock. For the patients with severe ARDS whose conditions cannot be improved or even deteriorate under conventional therapy, ECMO can provide a chance of survival.
Neonatal ECMO with Levitronix CentriMag: A Centrifugal Pump without Significant Hemolysis

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Introduction: ECMO is now routinely used for neonatal cardiac support. However, hemolysis caused by pump head or oxygenator failure remains one of the main problems of ECMO. The necessity to exchange part of the system such as pump or oxygenator during ECMO may well lead to severe drawbacks to recovery in patients who are totally dependent on ventricular support.

We report our initial experience in four neonates before and after cardiac surgery with the Levitronix CentriMag blood pump, a new device that aims to provide hemodynamic support without causing significant blood trauma. It is unique compared to other devices in that it is designed to operate without mechanical bearings or seals.

Methods: 4 neonatal cardiac patients were supported with the Levitronix CentriMag centrifugal pump over a range of 6-12 days. In Patient 1 the neck vessels were cannulated during cardiac resuscitation, patients 2-4 received chest cannulation after cardiac surgery. All patients were supported with high ECMO flow (170-240 ml/kg/min). Free plasma hemoglobin (FPH) levels were measured daily. All patients received hemofiltration. See Table 1 for patient and treatment details:

<table>
<thead>
<tr>
<th>Patient</th>
<th>Weight (kg)</th>
<th>Diagnosis</th>
<th>Max. RPM</th>
<th>ECMO Flow (ml/kg/min)</th>
<th>Pressure V/A (mmHg)</th>
<th>Cannula Size V/A</th>
<th>Days of Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2</td>
<td>pulmonary atresia + VSD after cardiac arrest</td>
<td>3700</td>
<td>200</td>
<td>-25/+250</td>
<td>8/6</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>3.3</td>
<td>hypoplastic right heart + TGA after Norwood I</td>
<td>3400</td>
<td>240</td>
<td>-30/+210</td>
<td>12/8</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>total anomalous pulmonary venous return after correction</td>
<td>4100</td>
<td>220</td>
<td>-45/+220</td>
<td>10/6</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>2.8</td>
<td>Taussig-Bing after switch and VSD closure</td>
<td>3500</td>
<td>170</td>
<td>-35/+180</td>
<td>12/8</td>
<td>12</td>
</tr>
</tbody>
</table>

Max.RPM: maximal rotations per minute, V/A: venous/arterial, VSD: ventricular septal defect

Results: All ECMO runs were technically uneventful. Even with hemofiltration included in the ECMO setup hemolysis was low without the need to exchange a part of the machine. Patients 2 and 3 were successfully weaned from ECMO. Patient 1 died from brain hemorrhage. Weaning was not successful for Patient 4 (Table 2).

Conclusions: This initial experience provides evidence that this new design centrifugal pump can alleviate the problem of hemolysis during ECMO in neonatal patients before and after cardiac surgery. To our knowledge no prior use of the CentriMag centrifugal blood pump in neonatal cardiac patients has been reported.

![FIGURE 1: FPH levels over ECMO support days](image1.png)

Table 2:
DIDECMO: A New Polymethyl Pentene Oxygenator for Pediatric ECMO

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Objective:
The purpose of this investigation was to review the performance of a new polymethylpentene oxygenator (DIDECMO, Dideco, Mirandola, Italy) in terms of clinical safety, efficiency in priming and oxygenation, and resistance of the membranes in neonatal and pediatric extracorporeal membrane oxygenation (ECMO) patients.

Device Description:
DIDECMO is a new phosphoricoline coated polymethylpentene hollow fiber membrane oxygenator for prolonged use in ECMO patients. It is certified for chronic use up to 5 days. The maximum blood flow rate is up to 2300 ml/min with a membrane surface area of 0.67 m². The static priming volume of the oxygenator is approximately 100 ml.

Methods:
Between March 2005 and January 2006, 14 patients required ECMO in the San Vincenzo Hospital. Eight patients (median age 9 days, range 3 days – 15 months) received normothermic ECMO for postcardiotomy heart failure after surgery for congenital heart disease. The DIDECMO oxygenator was used in all patients (median weight 2.4 kg, range 2 – 7 kg). All patients received the identical anticoagulation protocol and pulsatile flow.

Results:
Mean duration of support was 105 hours (range 26 - 198 hours). No oxygenator was changed during ECMO support. Median pressure drop of the oxygenator was 24 mmHg. No oxygenator related complications occurred.

Conclusion:
In our initial experience, the new polymethyl pentene DIDECMO oxygenator provided adequate gas exchange and had technical advantages in terms of low priming volume and acceptable pressure drop of the membrane with pulsatile flow.
Use of a Novel Anticoagulation Strategy During ECMO in Pediatric Population: Single Center Experience.

Objective:
Bleeding and thromboembolism remain the two most common early complications of Extracorporeal Membrane Oxygenation (ECMO). The purpose of this report is to describe a novel anticoagulation strategy with continuous intravenous antithrombin infusion and intermittent heparin infusion in pediatric population during ECMO.

Methods:
From November 2004 through February 2006, eleven patients required ECMO for post-cardiotomy cardiorespiratory failure. The mean duration of support time was 112 hours (range 65 - 198 hours). The following anticoagulation protocol was used in the first five patients:

1. heparin neutralization was achieved with protamine (1:1) upon discontinuation of cardiopulmonary bypass (CPB), before switch to ECMO.
2. target antithrombin level was not smaller than 60%: 60 (target value) – (Antithrombin value on lab test) x weight (bolus);
3. continuous heparin infusion (10 – 20 U.I./kg/h) was started via the oxygenator: (target ACT was180 – 200 seconds)
4. Tranexamic acid level was 10 mg/Kg (bolus) at the time of ECMO cannulation and then reduced to 1-3 mg/kg/h continuous up to 96 hours.
5. Hematocrit levels were maintained between 35% and 40% by continuous infusion of red blood concentrate at 5 ml/h up to target value.
6. Platelets counts were maintained not smaller than 100.000 mm\(^3\) by continuous infusion of concentrate platelets at 5 ml/h up to target value.

Since April 2005, we have changed our anticoagulation protocol: the following modifications were done in the last 6 patients:

7. Continuous anti-thrombin infusion was started immediately after surgery based on the lab result. The anti-thrombin level was maintained larger than 100%. The following formula was used: 100 (target value) – (Antithrombin value on lab test) x weight in four hours. Anti-thrombin value was checked at four hour intervals.
8. Heparin infusion was started when the anti-thrombin value was larger than 100%, and remained stable for more than 12 hours and the amount of bleeding was less than 2 ml/kg for more than 3 consecutive hours; then heparin infusion was started at 2 U.I./kg/h via the oxygenator, (target ACT was not smaller than 150 seconds).

Results:
Three patients expired in the first group. Eight patients were weaned and discharged. 3\(^{rd}\), 4\(^{th}\) and 5\(^{th}\) required surgical revision for bleeding. One of them experienced minor neurologic sequelae. No surgical revision or thromboembolic complications occurred in the new anticoagulation group.

Conclusion:
A novel anticoagulation strategy utilizing continuous intravenous antithrombin and intermittent heparin infusion significantly reduced surgical revision for bleeding in the first 48 hours. This has translated into excellent overall outcomes.
Introduction:
Since recirculation in dual lumen veno-venous ECMO reduces oxygen delivery to the patient, quantification of recirculation may be helpful in improving patient care. The currently accepted technique for measuring recirculation uses blood saturations and is not practical during VV-ECMO. A technique, dilutional ultrasound, may provide less invasive and more rapid, bedside determination of recirculation. The purpose of this study is to evaluate this technique in optimization of oxygen delivery.

Methods.
VV ECMO was initiated in two sheep (10-15kgs) using an Origen 15 Fr. dual lumen catheter advanced to the right atrium.. Ultrasound flow-dilution sensors H6XL, were clamped onto the inflow (arterial) and outflow (venous) ECMO tubing.

Results:
Data is presented in Fig.1 and Fig.2. Recirculation appeared to have a complicated relationship with the pump flow (Fig.1). Simultaneous repositioning of the catheter may dramatically improve catheter performance by decreasing recirculation and also improving delivered pump flow (Fig.2).

Conclusion:
Simplicity and quantitative assessment of recirculation by ultrasound dilution has a potential to improve catheter performance (decrease recirculation, while increasing or maintaining the same pump flow) by controlled altering of catheter location and orientation. This will lead to optimizing catheter performance during VV-ECMO procedures.
Unrehearsed Circuit Failure during Neonatal ECMO: Critical Trans – Heat Exchanger Pressure

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**Introduction:** Regular practice of emergency drills and rehearsal of familiar failure scenarios during cardiopulmonary bypass (CPB) or extra corporeal life support (ECLS) can prove useful when faced with a situation requiring rapid remedial action. Notwithstanding this, the possibility of an unforeseen critical incident is ever present and poses a threat to the safety of a patient.

**Case History:** A two-week–old baby girl with an unbalanced atrioventricular septal defect (AVSD) underwent corrective surgery with moderately hypothermic CPB. The patient could not be weaned from bypass and was placed on AV ECMO. Physiological and mechanical parameters improved over the next 36 hours in the intensive care unit. At this point a sudden violent gush of water was observed from the heater cooler system at the point where the outlet tubing had become detached from the machine. Fortunately there was no electrical power damage caused by the explosion. It was quickly established that this event had been caused by a massive pressure buildup at the integrated ECMO heat exchanger leading to immediate concerns for the integrity of the blood water barrier in the heat exchanger.

A series of attempts were made to identify the cause of the problem and thus rectify the situation: changing the heater cooler system, reversal of water flow through the heat exchanger and finally, a bridge between the outlet and inlet water tubing to moderate flow through the device. The result of this final intervention was that a complete circuit change out and the associated risks were avoided, and the patient was successfully weaned from ECMO after 83 hours.

**Discussion:** The incident described here is an example of a critical incident having its origin in ‘upstream’ systemic factors. The scenario was unfamiliar since it or another similar incident has not been previously reported and so presented the Perfusionist with a novel challenge. Subsequent analysis of this incident, which can be regarded as a ‘free lesson’ yielded valuable information. Three key elements were identified as factors in this systems failure: heater cooler system cleaning protocol, heat exchange device construction and incongruous heater cooler system application, which together, under these exact conditions contributed to creating a situation with the realistic potential for a negative outcome.

Modified CPB Circuit for Postoperative Rescue of High-Risk Patients Following Cardiac Repair: Are We Keeping Safe?

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Nemours Cardiac Center. Alfred I. duPont Hospital for Children. Wilmington, DE, USA

Introduction:
Extracorporeal membrane oxygenation (ECMO) is the mechanical circulatory support system most commonly used to treat post-cardiotomy cardiopulmonary dysfunction in small children. System readiness, ease of priming, need for additional blood products, excessive anticoagulation, and exposure to new surfaces are some of the important considerations, particularly when employed for resuscitation.

Methods:
We reviewed our institutional experience with the use of a cardiopulmonary bypass system which was modified to provide extended circulatory support system postoperatively in patients considered high-risk. The system included a Minimax Plus oxygenator, heparin-coated circuit with a 3/16 arterial and venous loop, roller pump (Cobe S-3) and open venous/cardiotomy reservoir. Once surgery was completed, the cardiotomy reservoir was removed from the circuit converting to extended support. If ECMO was not instituted, cannulas were removed, the arterial-venous loop was closed under sterile conditions and the system was recirculated for 24 hrs. Prior to discarding, blood samples were obtained for activated clotting time, arterial blood gas and blood cultures from 10 circuits.

Results:
Between 1/04 and 12/05 40 patients underwent cardiac repair using this CPB system. Procedures included Stage I Norwood, Truncus repair, combined Norwood Stage I & II, Interrupted aortic arch/VSD, Arterial switch/VSD/Arch repair. ECMO support was initiated in the OR in 7 patients, and three circuits were used after patient arrival in the ICU. Blood sampling after 24 hrs on stand-by circuits revealed a median pH 7.34 (7.14-7.41), PaO2 202mm Hg (136-224), hematocrit 32% (23-41), Ionized calcium 0.86 mmol/l (0.3-1.06), Potassium level 4.7 (3.6-5.6), ACT 550 (270-1000). All blood cultures were negative at 5 days. Overall survival to hospital discharge was 55%. There were no deaths among patients who received a circuit on stand-by.

Conclusions:
The cardiopulmonary circuit can be transformed into an simple, safe and effective ECMO support system. Deployment of a CPB circuit previously used for cardiac repair is immediately available, does not require priming, reduces blood use, avoids exposure to new surfaces, the risk of excessive anticoagulation and maximizes utilization of resources.
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

**Aristotle Score Predicts Outcome in Patients Requiring Extracorporeal Circulatory Support Following Repair of Congenital Heart Disease**

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Nemours Cardiac Center, Alfred I. duPont Hospital for Children, Wilmington, DE

**Introduction:**
Extracorporeal circulatory support (ECCS) has become the standard technique of mechanical support for the failing circulation following repair of congenital heart lesions. The objective of this study was to identify predictors of survival in patients requiring postcardiotomy ECCS. The Aristotle score, a method developed to evaluate quality of care based on complexity, was investigated as a potential predictor of outcome.

**Methods:**
Between 2003 and 2005, 37 patients required ECCS following corrective surgery for congenital heart disease. Records were reviewed retrospectively with emphasis on factors affecting survival to discharge. The comprehensive Aristotle complexity score was calculated for each patient.

**Results:**
Overall, 28 patients (76%) survived to decannulation and 17 patients (46%) survived to discharge. There were 24 (65%) neonates and 10 (27%) with single ventricle physiology, with a hospital survival of 42% (10 of 24) and 50% (5 of 10) respectively. Univariate factors associated with survival included Aristotle score, duration of support, reexploration, multiple organ failure and number of complications. Age, weight and single ventricle physiology were not significant. In a logistic regression model, an Aristotle score < 14 was identified as a predictor of survival (OR 0.12, CI 0.02-0.87).

**Conclusions:**
The Aristotle score is predictive of outcome in patients requiring postcardiotomy ECCS and may serve as a uniform criterion when comparing and evaluating quality of care and performance in this complex patient population.
The Effect of Flow Rate, Negative Pressure and Duration of Modified Ultrafiltration on Hemodynamics and Inflammatory Mediators

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Objective
The objective of this study is to evaluate the effect of flow rate, negative pressure and duration on Modified ultrafiltration (MUF) in hemodynamics and some inflammatory mediators.

Patients and Methods
Eighty children were randomly divided into four groups: group C, conventional MUF (10-20ml/kg.min, 0-30mmHg); group H, high flow rate MUF (10-50ml/kg.min, 0-30mmHg); group P, high negative pressure MUF (10-20ml/kg.min, 0-100mmHg); and group L, 15 minutes high flow rate MUF (10-50ml/kg.min, 0-30mmHg), whereas MUF was stopped when most of the blood remained in circulation pumped to the patients in other groups. During MUF, the flow rate and negative pressure were gradually increased. Hematocrit, heart rate, and blood pressure were recorded, and tumour necrosis factor (TNF), interleukin-6 (IL-6) were measured pre-bypass, at the cessation of CPB and MUF.

Results
The durations of MUF in group H and P were significantly shorter than the other two groups. The volume filtered in group L, 766.25 ± 119.85ml, was much more than the other three groups (about 400ml). The tendency of heart rate, blood pressure, and hematocrit during ultrafiltration were similar in all four groups (Table 1). The increases of the mediators were by far lower in L group, (Table 2).

Conclusion
Gradually increasing the MUF flow rate or negative pressure to certain extent is safe and can shorten the MUF time. This study also suggested that prolonging the duration of MUF filter out more inflammatory mediators.

Table 1. The change of HCT, heart rate and blood pressure

<table>
<thead>
<tr>
<th>Item</th>
<th>CPB stop</th>
<th>MUF 5 minutes</th>
<th>MUF 10 minutes</th>
<th>MUF stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCT (%)</td>
<td>Group C</td>
<td>24.43±1.90</td>
<td>28.40±2.07*</td>
<td>32.40±2.41*</td>
</tr>
<tr>
<td></td>
<td>Group H</td>
<td>24.30±1.73</td>
<td>31.67±2.52</td>
<td>35.66±1.15</td>
</tr>
<tr>
<td></td>
<td>Group P</td>
<td>25.67±1.86</td>
<td>30.67±2.30</td>
<td>35.25±4.57</td>
</tr>
<tr>
<td></td>
<td>Group L</td>
<td>23.60±2.30</td>
<td>30.25±3.40</td>
<td></td>
</tr>
<tr>
<td>Heart rate (bmp)</td>
<td>Group C</td>
<td>166.63±25.47</td>
<td>149.25±31.88</td>
<td>146.88±30.54</td>
</tr>
<tr>
<td></td>
<td>Group H</td>
<td>176.50±29.32</td>
<td>157.00±19.44</td>
<td>152.67±19.81</td>
</tr>
<tr>
<td></td>
<td>Group P</td>
<td>170.22±15.00</td>
<td>162.44±21.15</td>
<td>162.67±17.24*</td>
</tr>
<tr>
<td></td>
<td>Group L</td>
<td>154.75±24.33</td>
<td>150.75±16.58</td>
<td>150.00±10.52</td>
</tr>
<tr>
<td>Arterial systolic pressure (mmHg)</td>
<td>Group C</td>
<td>53.13±8.49</td>
<td>65.38±6.41</td>
<td>69.87±9.63</td>
</tr>
<tr>
<td></td>
<td>Group H</td>
<td>56.33±11.43</td>
<td>70.33±10.01</td>
<td>71.00±8.85</td>
</tr>
<tr>
<td></td>
<td>Group P</td>
<td>60.78±11.04</td>
<td>76.00±9.27*</td>
<td>78.22±11.44</td>
</tr>
<tr>
<td></td>
<td>Group L</td>
<td>53.13±7.67</td>
<td>68.25±13.51</td>
<td>73.38±12.60</td>
</tr>
</tbody>
</table>

* compared with other group in the same time, p<0.05
Table 2. The change of TNF and IL-6

<table>
<thead>
<tr>
<th>Item</th>
<th>Pre-operation</th>
<th>CPB stop</th>
<th>MUF stop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TNF (ug/ml)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group C</td>
<td>0.71±0.17</td>
<td>1.19±0.35</td>
<td>1.61±0.44</td>
</tr>
<tr>
<td>Group H</td>
<td>0.69±0.19</td>
<td>1.29±0.38</td>
<td>1.76±0.41</td>
</tr>
<tr>
<td>Group P</td>
<td>0.65±0.21</td>
<td>1.20±0.36</td>
<td>1.74±0.54</td>
</tr>
<tr>
<td>Group L</td>
<td>0.70±0.21</td>
<td>1.44±0.34*</td>
<td>1.61±0.30</td>
</tr>
<tr>
<td><strong>IL-6 (ug/ml)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group C</td>
<td>102.51±20.58</td>
<td>135.93±33.13</td>
<td>187.42±50.32</td>
</tr>
<tr>
<td>Group H</td>
<td>96.94±15.08</td>
<td>143.28±30.16</td>
<td>199.24±51.97</td>
</tr>
<tr>
<td>Group P</td>
<td>92.96±24.80</td>
<td>133.23±36.80</td>
<td>195.42±63.51</td>
</tr>
<tr>
<td>Group L</td>
<td>105.28±22.86</td>
<td>153.51±38.49</td>
<td>162.41±27.85*</td>
</tr>
</tbody>
</table>

* compared with other group in the same time, p<0.05
Advantages of Temporary Venoatrial Shunt Using Centrifugal Pump During Bidirectional Cavopulmonary Shunt in Small Children

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Introduction:
Single-ventricle palliation without use of cardiopulmonary bypass carries advantages that reduce systemic edema and inflammatory responses; however, simple clamping of the superior vena cava (SVC) without a temporary shunt leads to increase in cerebral venous pressure and subsequent decrease in cerebral blood flow during bidirectional cavopulmonary shunt (BCPS). We report our experience of BCPS using a temporary shunt system assisted by a centrifugal pump.

Methods:
The criteria for case selection include an unrestrictive atrial septal defect, no atrioventricular valve regurgitation, and the existence of an antegrade pulmonary blood flow. Since August 2000, 14 children with single ventricle physiology met the criteria. The mean age was 1.0±0.9 years and the mean weight was 8.4±2.6 kg. A temporary shunt was established between the SVC and the right atrium with right-angle cannulae, which were connected to a centrifugal pump to accelerate the blood flow from the SVC to the right atrium. The SVC pressure was continuously monitored during anastomosis.

Results:
All patients tolerated the procedure. The mean assist time was 22±5 minutes and the mean pump flow was 678±290 mL/min. Mean central venous pressure was 17±4 mmHg during anastomosis. The arterial pH, arterial pO2 and the transcutaneous oxygen saturation were maintained at 7.3±0.1, 43±9.0 mmHg and 77±8% during anastomosis, respectively. No patients required blood transfusion during the procedure. There were no postoperative neurologic complications.

Conclusions:
This study indicated safety and feasibility of the temporary shunt using a centrifugal pump for BCPS in small children. Further study should be done to elucidate the less invasiveness of this procedure over conventional BCPS using cardiopulmonary bypass.
Postoperative Prophylactic Peritoneal Dialysis in Neonates and Infants After Complex Congenital Cardiac Surgery

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Introduction:
Peritoneal dialysis after complex congenital cardiac surgery was introduced to a group of neonates and infants (n = 756, age: 0-1 years) between May 1993 and December 2005. Indications of peritoneal dialysis were determined as well as methods, prolonged dialysis and its outcomes.

Material and method:
Demographic characteristics, preoperative risk factors, intraoperative variables and postoperative complications were compared in 756 cases with ages below one year. All cases underwent modified ultrafiltration during perioperative stage. 186 cases (24.6 % of total) required peritoneal dialysis (in addition to perioperative modified ultrafiltration). The cardiac pathology was TGA in 133 cases, TOF in 37, IAA-APW in 4, and TAPVR in 5 and other complex pathology in 7 cases. Those patients who required perioperative ventilation, cases that had long bypass and TCA (total circulatory arrest) durations due to their complex pathologic conditions and those experiencing pulmonary hypertensive (PH) crisis were defined as “high risk group”. Prolonged peritoneal dialysis was usually required in infants with low-weight, with episodes of PH crisis (p<0.05), and with preoperative renal dysfunction. No major complication (peritonitis or hemodynamic instability) was observed related to the peritoneal dialysis catheter (during the use or following the withdrawal).

Results:
23 of 186 patients (12.3 %) had ARF and 4 of them died (2.15 % of all patients underwent operation, 17.3% of those with ARF). It has been demonstrated that the combination of peritoneal dialysis with perioperative modified ultrafiltration application was effective in providing the required postoperative negative fluid balance in especially complex congenital pathologic cases affected the survival positively.

Conclusions:
Protection of the renal functions and its maintenance therapy, which is an important factor in postoperative morbidity and mortality, can be safely and effectively done by prophylactic perioperatively initiated peritoneal dialysis in complex cardiac pathologies in neonatal period.

| Age (day) | 11 (2-72) |
| weight (kg) | 3.6 (1.8-5.5) |
| PD timing (postop.hour) | 8 (4-20) |
| Total fluid intake (cc/kg/day) | 106 (50-180) |
| Total fluid output (cc/kg/day) | 218 (130-560) |
| - Diuresis | 90 (35-180) |
| - PD UF | 115 (40-300) |
| Negative fluid balance (cc/kg/day) | 128 (60-320) |

Table 1. Features of patients

<table>
<thead>
<tr>
<th>Pre-PD</th>
<th>Post-PD</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum creatinine level (mg/dl)</td>
<td>0.76</td>
<td>0.79</td>
</tr>
<tr>
<td>Mean urine output (cc/kg/h)</td>
<td>2.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Mean number of inotropics agents</td>
<td>2.15</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 2. Parameters of pre- and post PD period
Anoxic Ventilation Improves Systemic Perfusion during Extracorporeal Circulation with Uncontrolled Systemic-to-Pulmonary Shunt

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Introduction: Uncontrolled systemic to pulmonary shunt, such as exists in preoperative truncus arteriosus or in postoperative modified Blalock shunt, results in decreased systemic blood flow during extracorporeal circulatory support and has been considered a relative contraindication. Control of such systemic-to-pulmonary shunts is not always readily achieved. In ex vivo preparations, alveolar hypoxia results in pulmonary vasoconstriction which continues to increase as inspired oxygen concentration is reduced below levels compatible with survival in the absence of circulatory support. We sought to determine whether anoxic (>99% nitrogen) ventilation would result in a non-invasive means of reducing pulmonary shunting during extracorporeal support in patients with uncontrolled systemic-to-pulmonary shunt.

Methods: Four weaned piglets were placed on open-chest cardiopulmonary bypass. Both the right and left atrium were connected to venous drainage. Then, a surgical shunt was created between the bicarotid trunk and the main pulmonary artery using 5 mm ePTFE tubing. The inspired oxygen concentration was gradually reduced to pure nitrogen and stabilized for 10 minutes, then returned to room air. pH, hematocrit, temperature, peak inspiratory and end expiratory pressures, and total pump flow were maintained constant. Hemoglobin oxygen saturation and flow volume of the right atrial venous return were measured as evidence of the amount and the adequacy of systemic perfusion.

Results: Systemic flow was significantly decreased upon unclamping of the systemic-to-pulmonary shunt, as shown by decreased right atrial return (278 vs. 475 ml/min, p<0.05) and decreased right atrial saturation (48% vs. 67%, p<0.05). Anoxic Ventilation (>99% nitrogen) resulted in partial, but potentially important, restoration of systemic flow (335 vs. 278 ml/min, p<0.05) and oxygen delivery (53% vs. 48%, p = 0.13).
The options for mechanical circulatory support for children in the United States are currently limited to extracorporeal membrane oxygenator (ECMO) circuits, an extracorporeal pneumatic VAD of varying size, and ventricular assist devices (VADs) designed and approved for adults. ECMO is the most commonly used form of circulatory support in children with approximately 500 cases/year reported in the Extracorporeal Life Support Registry. While ECMO can be used for support of children of any age, these circuits are largely limited to acute support of only a few weeks. The extracorporeal pneumatic device, the Berlin Heart Excor VAD, is available in sizes from 10 ml to 80 ml and can be used to provide support for neonates, children, and adults. However, in the US, the device is only available for emergency use in children with approval from FDA required before each implant, and exposed patients to the substantial risk of serious adverse events associated with these devices. Of the VADs designed for adults, devices such as the Thoratec VAD, the Heartmate XVE, and the Abiomed BVS 5000 have been successfully used in older children. The smaller adult VADs such as the MicroMed DeBakey VAD, the Jarvik 2000 Flowmaker, and the Heartmate II VAD provide additional options for pediatric patients as small as those with a BSA of 1.2 m$^2$. In addition, the MicroMed DeBakey VAD is available with reconfigured cannulae so that it can be implanted in children as young as five years old with BSAs as small as 0.7 m$^2$. The device, known as the MicroMed DeBakey VAD Child, is the only intracorporeal mechanical circulatory support device available in the US exclusively for children.

Despite the number of devices available for pediatric circulatory support, options for children under the age of five are severely limited. For this population, ECMO only provides acute support, available VADs for adults as well as the DeBakey VAD Child are too large, and an appropriately sized Berlin Heart Excor VAD requires approval on a case-by-case basis and is limited by its older technology. However, the need for devices that serve this population is great. In the US, nearly 1800 infants with congenital heart disease die each year and approximately 350 children under one year of age develop cardiomyopathy requiring heart transplantation. Of the 1600 children less than a year old who were added to the UNOS heart or heart/lung transplant lists over the past decade, less than half received a donor organ.

Appropriate mechanical circulatory support in these small, vulnerable patients is expected to improve outcomes. With currently available heart pumps, the efficiency of organ utilization in children has improved and some children who experienced acute fulminant myocarditis or postcardiotomy syndrome have been successfully bridged to recovery. However, the anticipated improvement in outcomes in the youngest patients cannot be realized until suitable devices are developed to provide safe, chronic support to successfully bridge them to transplant or recovery.
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

Current Progress in the Development of the PediaFlow™ Pediatric Ventricular Assist Device

Harvey Borovetz, Ph.D., Dorian Arnold, B.S., Tim Bachmann, B.S., Stephen Badylak, D.V.M., M.D., Ph.D., J. Robert Boston, Ph.D., Carl Johnson, B.S., Robert Kormos, M.D., Marina Kameneva, Ph.D., Marwan Simaan, Ph.D., Trevor Snyder, B.S., Hiro Tsukui, M.D., Bronwyn Uber, B.S., William Wagner, Ph.D. and Josh Woolley, B.S., Bioengineering & McGowan Institute of Regenerative Medicine, University of Pittsburgh; James Antaki, Ph.D. Arielle Drummond, M.S., James Donachy, Jr., B.S., Fangjun Shu, Ph.D. and Stijn Vandenberghe, Ph.D., Biomedical Engineering, Carnegie Mellon University; Bradley Keller, M.D., Victor Morell, M.D., Peter Wearden, M.D., Ph.D. and Steven Webber, M.D., Children’s Hospital of Pittsburgh; Jeff Gardiner, B.S., Chung M Li, Ph.D., Dave Paden, B.S., Bradley Paden, Ph.D., Shaun Snyder, B.S., Josiah Verkaik, B.S. and Jingchun Wu, Ph.D., LaunchPoint LLC, Goleta, CA; Gill B. Bearinson, Ph.D., Gordon Jacobs, M.S., John Kirk, M.B.A., Pratap Khanwilkar, Ph.D., Jim Lee, M.S., James W Long, M.D., Ph.D., Tim Maher, M.S, and Phillip Miller, M.S., World Heart Corporation, Salt Lake City, UT; John A Hawkins, M.D., Peter C. Kouretas, M.D., Ph.D., and R E Shaddy, M.D., Primary Children’s Medical Center, Salt Lake City, UT.

Introduction: The PediaFlow™ is a mixed flow turbodynamic pump, incorporating a magnetically levitated impeller, intended to provide 0.3 to 1.5 liters per minute of blood flow with minimal anticoagulation for neonates and infants requiring cardiac support.

Methods: The motor and suspension were designed to optimize space utilization while generating adequate suspension robustness and motor torque development. The fluid path was optimized through progressive refinement of the impeller and stator geometry by computational fluid dynamic analysis to insure the pump could generate the specified flow rates at physiologic pressures. Fore and aft sensors were developed to monitor pump performance. Following completion of the fluid path, motor, suspension, and sensor designs; the generation 1 (GEN 1) fabrication design was completed, adding cannula connectors and sewing eyelets. The pump controller has been modified from the Streamliner, which shares the same topology. Validation of predicted performance characteristics was performed as components are fabricated.

Other areas of investigation include anatomic fit modeling, cannula development, thermal modeling, biocompatibility, and developing a pediatric mock flow loop capable of modeling the diverse anatomic anomalies expected to be encountered.

Results: Fabrication and assembly of initial component revealed small variations from model predictions. The empirical analysis was used to refine the mathematical models for input into planned generation 2 (GEN 2) development. Stator vane thickness was increased to facilitate manufacturing. Some modifications to the mechanical design were required to insures device integrity under applied stresses (e.g. at implantation). Sensor testing demonstrated a 0.05 μm sensitivity, well within the required range for axial control of the impeller.

Thermal modeling predicts the GEN1 prototype will have acceptable heat generation. Preliminary anatomic models have been generated. Additional patient images are being obtained to expand the effort. Assays to quantify ovine (the intended animal model) blood cell activation, aggregation, and platelet life span have been developed. The pediatric mock flow loop successfully demonstrated ventricular suction and collapse and will continue to undergo refinement.

Conclusion: The GEN1 PediaFlow™ blood pump has been developed and is proceeding through fabrication and model and performance verification and validation. The completed prototypes will begin animal trials in Q2 of 2006. Incorporation of model refinements and further miniaturization are planned for the GEN2 design. The intensive analysis and optimization of the PediaFlow™ will ultimately produce an optimally biocompatible blood pump, capable of supporting neonates and infants by providing bridge-to-transplant or cardiac recovery support.

Supported in part by NIH Contract NO1-HV-48192.
The Penn State Pulsatile Pediatric VAD

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Development of the Penn State Pediatric VAD is currently focused on the 12 ml stroke volume device for infants. The following is a summary of recently completed and current activities.

During the past year, pump design was completed and prototypes were manufactured. First generation cannulae and connectors were also designed and manufactured.

Fluid mechanic studies are being performed to measure and interpret the flow field in (in vitro) models of the PVAD, to assess the potential for thrombosis and hemolysis on the basis of the flow, to try to correlate this potential with in vivo studies, and to assist in design modifications. The following factors are currently being investigated with PIV: Newtonian versus non-Newtonian blood analogs, inlet and outlet port geometry, valve orientation (rotation angle), valve type, and outlet valve location.

We have completed the development of non-Newtonian blood analogs. PIV results show the importance of using a non-Newtonian fluid in studying local fluid dynamics, which is especially important in small-sized pediatric devices. A study of clinical pediatric blood viscoelasticity measurements was also completed. The effect of hematocrit was shown to be an important factor in blood rheology. Differences between adult and pediatric blood were found to be minimal.

Blood sacs and test samples are being tested to investigate the effect of polymer type, solids concentration, and processing temperature on mechanical properties and surface morphology. Force-elongation testing is being performed and characteristic properties such as Young’s modulus, tensile strength, elongation to break and fracture energy are derived. Dynamic mechanical analysis is used to measure the modulus and mechanical loss as a function of temperature.

SEM and AFM analyses of surfaces and cross-sectioned sacs are being performed to check for voids or defects. Differential Scanning Calorimetry (DSC) is being used, along with Small Angle X-ray Scattering (SAXS), to characterize the chemical and phase structure of the polymers.

In preparation for implantation studies in animals, an in vivo study in lambs and goats was completed. The objective was to measure their normal hematologic parameters and to measure their response to anticoagulant and anti-platelet therapy.

An acute implantation was performed in a 15 kg male goat. The objectives of the study were to: 1) obtain pressure and flow data for comparison to mock circulatory loop data, 2) evaluate the surgical technique, cannulae, and tools required for implantation, 3) evaluate the operative procedure and anesthesia procedure, 4) obtain measurements of cannula lengths and positions required in the juvenile goat.

Platelet adhesion and coagulation assays are being used to compare polymers and fabrication parameters. Recent efforts have focused on developing AFM-based high resolution functional imaging.

Preparations have been completed for animal studies and durability studies to begin within the next 6 months.

Acknowledgements
This research is supported by the National Heart, Lung, and Blood Institute (NHLBI) Contract N01-HV-48191.
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

Infant and Child-Size Jarvik 2000 Hearts

Introduction: The NIH contract program to develop pediatric VADs is now in its third year. We have been miniaturizing intraventricular VADs for children and infants based on the characteristics of the adult-size Jarvik 2000 Heart. The adult device has proven highly reliable, with no blood pump failures in over 150 patients supported up to almost six years at present.

Both the child and infant models are intraventricular axial flow pumps utilizing blood immersed ceramic bearings. Although similar to the adult model, the small devices utilize significantly different design solutions to mechanical fabrication and assembly issues, as well as CFD studies, computational bearing analysis, and the biological interface relating to the very small size of the devices.

Presently, child size devices are undergoing animal tests in 20 Kg. lambs. Initial prototypes of infant size pumps are nearing completion and bearing analysis shows that the bearings of both child and infant sizes will be radially hydrodynamic at all speeds of operation.

Methods: Miniaturized pumps similar to the Jarvik 2000 were designed, fabricated, and tested to meet the design input specifications as included in the proposal and further defined under the program. The table below gives the properties of the 3 pumps. Figure 1 gives animal flow data on the Child model. Figure 2 is a photograph of the near complete infant model.

Conclusion: Child and infant Jarvik 2000 Hearts are proving to be feasible.

<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter (mm)</th>
<th>Length (cm)</th>
<th>Volume (cc)</th>
<th>Weight (g)</th>
<th>Graft (mm)</th>
<th>Speed (RPM)</th>
<th>Flow L/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult</td>
<td>26</td>
<td>7.8</td>
<td>30</td>
<td>90</td>
<td>16</td>
<td>8-12,000</td>
<td>1-6</td>
</tr>
<tr>
<td>Child</td>
<td>17.5</td>
<td>5.2</td>
<td>10</td>
<td>35</td>
<td>10</td>
<td>10-14,000</td>
<td>1-3</td>
</tr>
<tr>
<td>Infant</td>
<td>12.2</td>
<td>4.6</td>
<td>4</td>
<td>12</td>
<td>6</td>
<td>16-24,000</td>
<td>¼ - ¾</td>
</tr>
</tbody>
</table>

Figure 1. Average Child Model Flow in 3 lambs

Figure 2. The Infant Jarvik 2000 Prototype
Surface Modifications of Hollow Fiber Membranes as Applied to the Enson pCAS System

Mark Gartner, ME, Patrick Cahalan, BS, Linda Cahalan, Greg Johnson, PhD
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Introduction:
Ension’s pediatric cardiopulmonary assist system (pCAS) includes a coating designed to minimize blood/biomaterial interactions. Current bioactive coatings such as Carmeda have been considered but significantly hinder gas exchange when applied to hollow fiber membranes (HFMs). This impact on permeance, while not critical in current clinical oxygenators, is important to the pCAS system. Ension has begun a program to address this need by developing a heparin-based coating that improves bioactivity without dramatically decreasing fiber permeance. Three strategies for coupling heparin to HFMs have been explored using siloxane and allylmine, polyethyleneimine (PEI), polyethyleneoxide (PEO) as spacer molecules.

Methods:
Celgard X30-240 hollow fiber array was modified using a multi-step process that includes amination and functional heparinization. Amination and heparin deposition were assessed using staining techniques. Bioactivities of control and heparin-modified surfaces were assessed using a thrombin deactivation method that consists of exposing test surfaces to a solution containing ATIII and thrombin. The amount of active thrombin collected from the solution and in rinse solutions was determined by using a chromogenic substrate that is cleaved by active thrombin and generates a color that can be measured spectrophotometrically. Following confirmation of bioactivity, prototype devices were constructed for evaluation in a mock circulatory loop at Ension. Using fresh bovine blood as the working fluid, gas exchange of coated prototypes was evaluated and compared with uncoated controls.

Results:
Ponceau S staining showed a dark uniform pink stain confirming amination and Toluidine Blue staining showed a dark uniform purple stain confirming heparinization on all prototype coatings. Bioactivity assays have demonstrated activity on-par or greater than commercially available coatings. Gas exchange testing has indicated the fiber with siloxane-based coating best achieved our overall performance goals.

Conclusions:
Preliminary results suggest the heparin-based coating being developed by Ension demonstrates acceptable bioactivity and permeance for the pCAS application.
The PediPump™: A Versatile, Implantable Pediatric Ventricular Assist Device

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The Department of Biomedical Engineering, The Lerner Research Institute, Cleveland Clinic

The PediPump is a new ventricular assist device designed specifically for pediatric applications. The design is based on a rotary dynamic pump; an important aspect of the design is the absence of a seal with suspension of the rotor on magnetic bearings. The pump rotating assembly consists of an impeller in the front, front and rear radial magnetic bearings and a motor magnet in its center (see Figure). The pump measures approximately 7 mm X 75 mm with a priming volume of 0.6 ml which imparts less than 10% of the physical displacement of currently available axial flow pumps while retaining good flow capacity. The device provides pressure and flows capable of supporting adults, far exceeding the requirements for support of children in the 2 to 25 kg weight range. This basic pump design may be suitable for right ventricular, left ventricular or biventricular support; the pump may also be used in acute or chronic clinical settings.

The current development program for the PediPump includes three specific aims:

1) Determination of the basic engineering requirements for hardware and control logic including design analysis for system sizing, evaluation of control concepts and bench testing of prototypes.

2) Performance of pre-clinical anatomic fitting studies using CT-based 3D modeling.

3) Evaluation with animal studies to provide characterization and reliability testing of the device.

At the completion of studies in this proposal the following will have been achieved:

- Development and testing of a small pediatric VAD including the acquisition of initial multi-year durability data.
- Determination of deployment methods for the wide range of sizes and anatomic variation encountered in children with heart disease using 3D modeling techniques based on CT imaging.
- Documentation of the responsiveness and reliability of the pump in the implant environment and determination of the host response to the presence of the pump from animal implantations.

Figure: The PediPump: Arrows demonstrate path of blood flow from the inlet through side-ports in the device housing.
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In addition to the development of new pediatric mechanical circulatory device, the clinical experience of MCSD in children is rapidly expanding. Because individual experience at each center will be limited, the utility of a common registry will be invaluable to answer clinical and research questions over the next decade. In support of this effort, the National Institute of Health through the NHLBI has funded a 5 year, multi-million dollar effort to initiate, develop, and maintain a Registry database for MCSD in adults and children.

The Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) began its efforts in July of 2005 as a joint effort among the National Heart, Lung, and Blood Institute, the Centers for Medicare and Medicaid Services (CMS), the Food and Drug Administration, clinicians, scientists and industry representatives. INTERMACS is a national registry for patients who are receiving mechanical circulatory support device therapy to treat advanced heart failure. It is a unique collaboration with the central purpose of advancing the field of mechanical circulatory support and therefore, improving patient outcomes. All patients who receive a device for chronic mechanical circulatory support will be included.

The definitions of adverse events and the pediatric data fields have been approved by the FDA. The hope that the registry will limit data collection for the sites, for both industry initiated protocols as well as post-approval FDA requirements. The University of Alabama at Birmingham (UAB) is the Data Coordinating and Data Analysis Center and United Network for Organ Sharing (UNOS) is the Clinical Research Organization with responsibility for maintaining the database.

The objectives of INTERMACS include, but are not limited to the following:
1. To facilitate the refinement of patient selection for maximizing outcomes with current and new device options
2. To improve and expedite new device clinical trials by providing historical control data reliable enough to serve as Objective Performance Criteria (OPC) standards for FDA
3. To develop consensus "best practice" guidelines for improvement of clinical management by reducing short and long term complications of MCSD therapy.
4. To improve economic outcomes by identifying and optimizing factors affecting cost-effective therapy for cardiac failure patients
5. To use data and analysis to guide improvements in technology, particularly as next generation devices evolve
6. To promote research into the underlying pathophysiologic substrate of advanced heart failure by defining and promoting the conditions necessary for myocardial recovery

Initial initiatives, registry progress report, and opportunities for individual participation will be discussed.
Proteomics and Pediatric Cardiac Surgery

Vrana, KE	extsuperscript{1}, Lull ME	extsuperscript{1}, Freeman WM	extsuperscript{1}, Myers JL	extsuperscript{2}, Midgley F	extsuperscript{2}, Kimatian SJ	extsuperscript{3}, Ündar A	extsuperscript{2}

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2 Departments of Pediatrics, Surgery, and Bioengineering,
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Introduction:
A major challenge of pediatric research is the limited capability of obtaining tissue samples from small patients. To confront this problem, biomarkers found in blood can be used as surrogate markers of disease processes and aid in patient monitoring and disease detection. For example, cytokines measured from plasma act as a marker for tissue damage and inflammation. Furthermore, proteomic analysis of plasma samples may provide for large-scale discovery of disease biomarkers.

Objective:
The objective of this study is to characterize the proteomic profile of plasma from pediatric patients undergoing cardiopulmonary bypass (CPB) surgery. Baseline differences between patients with different severities of disease and changes resulting from surgery can be evaluated to identify differentially expressed proteins. Changes in these proteins can then be correlated with the degree of damage and/or clinical outcome.

Methods:
Heparinized blood was collected from patients undergoing cardiopulmonary bypass at five time points: before surgery (1), 5 minutes on bypass (2), at the conclusion of the surgery (3), 1 hour post-weaning from bypass (4), and 24 hours post-weaning (5). Blood was collected in EDTA vacutainers and cells were spun down at 1000g for 15 minutes at 4 degrees. Resulting plasma was depleted of six high-abundance proteins (albumin, haptoglobin, IgG heavy and light chains, antitrypsin and transferrin) to improve sensitivity to low abundance proteins. Depleted plasma, bound proteins, and whole plasma from baseline samples of two patients were each separated by their pI value using isoelectric focusing followed by a second dimension gel separation by molecular weight. These gels were stained with Sypro dye and imaged. Depleted samples from timepoints 2 and 4 were labeled with Cy3 and Cy5 dyes, respectively, and separated in two dimensions as above.

Results:
Depletion of patient plasma is consistent, and removes the desired proteins without affecting other protein species. The depletion process removes approximately 85% of the total protein. In addition, the process of depletion allows for an enrichment of the lower abundance plasma proteins that cannot be identified when using whole plasma. Baseline plasma samples from two patients, despite different clinical profiles, are very similar in protein expression.

Conclusions:
Plasma from pediatric cardiopulmonary bypass patients can be depleted of high abundance proteins that mask changes of small, but potentially important proteins. This process can be successfully used to examine protein changes that occur as a result of cardiopulmonary bypass. Observed changes may illuminate possible damage and remodeling occurring as a result of CPB.
From the outset, cardiac surgery developed by equal parts of imagination, innovation and courage. The desperate plight of critically ill patients drove the early attempts at salvaging life by almost any means. Surgeons recognized that in the absence of treatment, the outcome for many patients was early death. Anecdotal experience was the rule of the day and more than one case of anything really did make a series. Innovation preceded the invention of Institutional Review Boards (IRB).

In 1893, Dr. Daniel Hale Williams was first (it’s always dangerous to say who was “first”) to operate successfully on a patient with a cardiac wound. James Cornish, was the victim of a knifing. Williams observed that the laceration in the right ventricle had stopped bleeding and he simply sutured the pericardium. His real contribution was avoiding a wound infection by his routine of very careful antisepsis. Death by infection was the usual outcome prior to the advent of antibiotics.

Open heart surgery developed during the late 1940’s and early 50’s with many people attempting innovative techniques. Prior to the invention of cardiopulmonary bypass, open heart technique was by inflow occlusion that allowed a 3 minute interval to complete an intra-cardiac repair. The addition of hypothermia added more minutes. But with induced hypothermia came the controversy of whether the metabolic rate increased or decreased, and the complications of ventricular arrhythmias and/or bradycardia; the latter leading to the invention of external cardiac pacing. Each incremental step of progress involved identifying and solving new problems and capitalizing upon the progress in related fields of cardiology, anesthesia, and the advent of specialized recovery areas, the precursor of the critical care unit.

Cardiopulmonary bypass was considered in 1930, by the aviation pioneer Charles Lindberg and Nobel laureate Alexis Carrel. By 1935 they developed a pump that perfused organs with pulsatile flow and oxygenated perfusion fluid. But it was not until the 1950’s that cardio-pulmonary support capable of sustaining the entire patient was conceived. In early clinical use of the “pump” (not really clinical trials in the current context), surgeons coped with primitive equipment, misdiagnosis, and the poorly understood abnormal anatomy and physiology that their patients suffered from.

The present refinements in the care of cardiac patients are a testament to the success of the team of innovative health care workers and to the medical industry. The team produced a transition from a new high-risk & uncertain discipline to a commonplace, high volume, low-risk specialty with excellent outcomes. We should expect and encourage these innovations from within and from outside our specialty to continue to improve the care for our patients.
Highly successful pediatric transplantation has been taking place for 25 years. Successful neonatal transplantation has occurred for 20 years. Where are we now and what are the trends? Expanding the donor pool by increasing size mismatch, using hearts that have been resuscitated, and the use of more distant procurements has already been done to the limits of current technology. Our present challenge is to define problems whereby the expanded use of available technology will improve perioperative outcomes i.e. improving outcomes at the margins.

Early experience demonstrated a difference in outcomes for cardiomyopathy vs congenital lesions: Present outcomes indicate that that difference has been mitigated. But has it really been ameliorated? Our own experience and that of others indicates that those patients receiving transplantation for congenital lesions with previous palliation causing HLA sensitization/high PRA’s have a poor outcome with 25-50% early mortality (Jacobs JP Ann Thorac Surg 2004 Nov;78(5):1703-9). Mortality was high despite the use of exchange transfusions, plasmapheresis, and mycophenolate mofetil. We have shown that one of the issues in this high risk group is HLA sensitization from previous use of homograft material for arch reconstruction. Alterations in primary surgical strategy such as the use of all autologous tissue may be useful. Early experience with rituximab as a means of reducing panel-reactive antibodies holds potential. Patients who are at risk for a positive cross match have been limited to local donors. A virtual crossmatch as a screening tool for sensitized patients that has recently been reported (Zangwill SD Pediatr Transplant 2006 Feb;10(1):38-41). Further exploration of this strategy may expand the potential donors for a given patient. An awareness of race dependent outcomes that are independent of socioeconomic status is another potential area for improvement. (Mahle WT J Pediatr. 2005 Dec;147(6):721-3)

Neonatal or early infancy transplantation for hypoplastic left heart syndrome (HLHS) has been on the decline (Chrisant MR, JHLT 2005 May;24(5):576-82) but it is still performed for select indications or parent preference. The waiting list mortality of 25% is comparable to our data prior to the institution of an ABO incompatible transplantation strategy. Waiting list mortality for the neonatal population has approached zero by an effective expansion of the donor pool. (that expansion may be temporary as further institutions employ the strategy). Outcomes in the ABO incompatible group have been equivalent to the matched groups to date.

Resynchronization therapy is just emerging in the pediatric population as a means of improving systolic function. Current status is that of defining patients for whom it is a benefit. General indications for resynch therapy are significantly decreased ventricular function in association with conduction delay.

Retransplantation: UNOS data indicates a 1, 5, and 10 year survival of 79%, 53%, and 44% for pediatric retransplantation. Survival for those not on a ventilator and transplanted at greater than 180 days was statistically better than for the entire cohort. (Mahle WT, JTCVS 2005 Aug;130(2):542-6) Individual institution reporting for retransplantation can be more favorable indicating either a performance or selection improvement to outcomes.

True pediatric VAD, beyond ECMO, is recent in North America. Full acceptance and FDA or Health Canada approval is in process. Progress in those areas will be discussed by others at the meeting.

Summary:
Perioperative transplantation trends and improvements will be derived from working at the margins of outcomes – expanding the use of present knowledge and technology to leverage improvements.
Pediatric Heart Transplantation in Europe

Christoph Knosalla, MD, PhD and Roland Hetzer, MD, PhD
Berlin, Germany
Use of Mechanical Cardiac Assistance in Cardiac Transplantation: Evolving Practice

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Great Ormond Street Hospital for Children
London, United Kingdom

Development of assist programme
In 1998 our Institution adopted a policy of mechanical bridging of paediatric patients to cardiac transplantation. This decision was based on a 1996/7 audit of the UK Transplant Database that revealed that there was no absolute shortage of donor organs in the UK, but a mismatch between timing of availability of donor hearts and recipient demand. Because it was estimated that the average waiting time for an organ would be up to several months, we elected to use a paracorporeal ventricular assist device, with the expectation that cardiac support with end-organ recovery could ultimately take place outside the ITU. Unfortunately, the initial 4 patients supported on a paracorporeal assist device (MEDOS) had high complications rates and remained ventilator and inotrope dependent.

Since our Unit is also a supra-regional centre for extra-corporeal membrane oxygenation (ECMO) we decided from 1999 to use ECMO for mechanical bridging to transplantation. This strategy has been supplemented by the use of early transcutaneous balloon atrial septostomy, to offload the left heart and improve filling of the ECMO circuit. Because of the duration of an ECMO run is generally limited to several weeks, rather than months, a national policy of high priority listing for transplantation (equivalent to UNOS status 1A) was adopted for children on ECMO. In addition, the use of marginal and oversized donor hearts (up to 3x body weight) and more recently the introduction of ABO-incompatible transplantation (recipients anti-A or anti-B isohemagglutinin titers < 1:16) have improved access to the donor pool.

In 2004, we reintroduced the use of a paracorporeal assist device (Berlin Heart) in a patient who after an extended ECMO run (20 days + 19 days) developed complications of the neck cannulation site. The patient was subsequently extubated on the VAD and started rehabilitation during the subsequent waiting period of 66 days for transplantation. To date, the Berlin Heart LVAD has been used in 3 patients. All were extubated on the device, started mobilisation and underwent successful cardiac transplantation.

The timing for initiating mechanical assistance remains difficult, in particular since patients in severe heart failure are prone to sudden cardiac arrest. However, because of the complications inherent to mechanical assist devices and the costs too early insertion should be avoided. Our current policy is to move to a device if patients have an increasing inotrope requirement or develop signs of end-organ failure. If a short assist time is anticipated, or if there are questions about suitability for transplant, ECMO is used as a bridge to transplantation, recovery or bridge to later VAD.

In an acutely unstable patient or a cardiac arrest situation we have access to rapid response ECMO. It is our experience that if ECMO cannot be established within 30 min of initiating cardiopulmonary resuscitation, there is a very high incidence of severe brain damage, making further successful cardiac bridging unlikely.

In the absence of early indicators for cardiac recovery, the decision between bridging to recovery and bridging to transplantation remains very difficult. We do not currently perform routine biopsies to look for active myocarditis (except at time of implantation of the Berlin Heart), but screen for myocarditis.
### Assist episodes for cardiac failure 1998-2005 (incl)

<table>
<thead>
<tr>
<th>Patients &lt; 10 kg</th>
<th>Total</th>
<th>Weaned</th>
<th>Duration hrs (range)</th>
<th>Transplant</th>
<th>Duration</th>
<th>Died</th>
<th>Duration hrs (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMO</td>
<td>9</td>
<td>5</td>
<td>213 (84-405)</td>
<td></td>
<td></td>
<td>4</td>
<td>316 (187-442)</td>
</tr>
<tr>
<td>Patients &gt; 10 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECMO</td>
<td>34</td>
<td>5</td>
<td>179 (124-221)</td>
<td>26 (3 died post Tx)</td>
<td>216 (14-476)</td>
<td>3</td>
<td>342 (56-524)</td>
</tr>
<tr>
<td>MEDOS</td>
<td>4</td>
<td></td>
<td>2</td>
<td>89 - 210</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BH</td>
<td>3</td>
<td></td>
<td>3 *</td>
<td>640 (636-1584)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 2 had previous ECMO: 1 pt 2 episodes (476+448 hrs), 1 pt 1 episode (215 hrs)
Long-Term Outcome of Thoracic Transplantation in Pediatric Patients (and GUCH Patients)

Sabine Daebritz, MD
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Objective:
Retrospective review of patients undergoing orthotopic heart transplantation (HTx) or heart-and-lung-transplantation (HLTx) for congenital heart disease (CHD) and acquired heart disease (AHD) in a grown-up and pediatric population.

I : Analysis of outcome of GUCH HTx

Methods:
Since 1988, 13 HTx were performed in patients ≥16 years of age for CHD (group I; 7 male, mean age 26±11 years). They were compared to 605 patients ≥16 years of age with AHD (group II; 504 male, mean age 51±11) and to patients <16 years of age with CHD (group III; 10 male, mean age 13±5 years). Patients in group I were younger than in group II had more previous operations than in groups II and III.

Results:
Operative mortality was 31% in group I and was higher compared to group II (13%) (p=0.077) and III (0%) (p=0.035). Actuarial survival after 1, 5 and 10 years was 62%, 46% and 46% in group I and tended to be lower than in group II (79%, 72% and 59%) (p=0.059), and III (p=0.059). In the 30-day survivors, there was no difference in long-term survival between the groups after 1, 5 and 10 years: 89%, 71% and 71% (group I), 90.5%, 84% and 77% (group II) and 80%, 80% and 80% (group III) (n.s.). Previous cardiac operations were a risk factor for early mortality.

II Analysis of outcome of pediatric HTx

Methods:
The overall number of pediatric patients who underwent pHTx for any disease was 58, including 23 patients with CHD.

Results:
Operative mortality was 6.8%, late mortality was 12.1%, mainly caused by acute rejection and pneumonia. Mean follow-up was 5.2±4.2 years. Actuarial survival after 1, 5 and 10 years was 86%, 80% and 80% and improved significantly after 1995 to 92% and 92% (p=0.04). Survival was comparable between patients with or without CHD.

III Analysis of outcome of HLTx

Methods:
Long-term outcome of HLTx in pediatric patients (n=15) and in patients 18 years or older (n=50, mean age 33.6±9.7 years, 23 male) was analyzed comparing those with CHD (n=27, 54%) with patients with other cardiopulmonary diseases

Results:
Follow-up was 2.85±3.5 years. Actuarial survival after 1, 5 and 10 years was 54.6%, 23.4% and 11.7% for GUCH patients and comparable to the other patients (56.2%, 28.1% and 18.7%, respectively).

Pediatric patients: Follow-up was 7±2.7 years. Actuarial survival after 1, 5 and 10 years was 86.7%, 72.2% and 45.1%, respectively. Three patients developed lymphoma under immunosuppression, which has changed over time, but since 1995 consists of cyclosporine or tacrolimus combined with mycophenolat mophetil and corticosteroids.

Conclusion:
Patients with congenital heart disease undergoing HTx at the age ≥16 years are at increased risk for early mortality, but have comparable long-term outcome. The results of HLTx are independent of the underlying disease. Analysis of a larger cohort of adults with congenital heart disease is necessary to identify specific risk factors. Pediatric patients have excellent results after HTx and good results after HLTx.
Outcome of Heart Transplantation in 95 Pediatric Recipients

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Background:
Orthotopic heart transplantation (HTx) is last choice therapy in children with severe heart disease. In this study we reviewed the outcome of pediatric heart recipients with incorrigible heart diseases with Cylosporin A, Azathioprine and Glucocorticoids induction therapy.

Patients:
Between 1988 and January 2006 HTx was performed in 95 pediatric patients at an age of one week up to 16 years (mean 6.1 ± 5.1) in our center. Diagnoses were in 61 cases dilative cardiomyopathy and in 28 cases congenital heart disease. 6 patients underwent heart transplantation after myocarditis. 7 patients required mechanical support before HTx. The immunotherapy was based on triple drug therapy with Cyclosporine A, Azathioprine and Methylprednisolon following the reduction and adjustment of the necessary dosage. The acute rejections were detected non-invasively with echocardiography, rarely confirmed by right ventricular biopsy and treated primarily with steroid-pulse-therapy.

Results:
We observed 84 cases of acute rejection in 35 patients (41.6%). 29 patients were treated sufficiently in the above described manner. In 6 patients with severe and steroid-resistant acute rejection we administrated monoclonal antibody OKT3. Two patients survived. The cumulative survival was after one year 91% and after 10 years 89% for all patients. We observed 16 cases of renal insufficiency, one case of graftvasculopathy and one neoplastic disorder.

Conclusion:
Orthotopic heart transplantation as the only option for children with severe heart disease shows acceptable peroperative mortality and good long-term results. The induction of immunotherapy with Cylosporin A, Azathioprine and Glucocorticoids following the reduction and adjustment of the necessary dosage established a sufficient immunsuppressive shield in the early and late postoperative period.
Use of Extracorporeal Membrane Oxygenation (ECMO) as a Bridge to Pediatric Heart Transplantation

SM Pollock-BarZiv, R Perez, A Campbell, D Edgell, J Coles, LJ West, BW McCrindle, G VanArsdell and AI Dipchand.

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Background: ECMO is used as a salvage therapy for children with end stage cardiac disease who may be candidates for heart transplantation (HTx), although outcomes remain variable with few identified factors predictive of outcome. At the Hospital for Sick Children (HSC), ECMO has been utilized in selected patients (pts) with myocardial failure since 1990, with intention of bridging to subsequent HTx. We sought to describe outcomes of early mortality and morbidity, and to determine risk factors for pts waitlisted for HTx from ECMO.

Results: There were 205 pts supported with cardiac ECMO from Jan 1990 to Dec 2005, of whom 46 were wait-listed for HTx. Sixteen pts died while wait-listed on ECMO; 5 were delisted due to improved clinical status, and 25 pts underwent HTx from ECMO (12 males). Of the 25 HTx pts [median age of 7.0 yrs (range: 10 days - 17 yrs)], 13 had a primary diagnosis of myocarditis or cardiomyopathy, and 12 had congenital heart disease (4 single ventricle physiology, 4 aortic valvar lesions, 4 other anomalies; 2 were bridged to HTx #2). The median duration of ECMO was 6.7 +/- 4.6 days [range 3-18 days]. Median follow up was 2.8 yrs (0 to 10.2 yrs). Four pts died within 1 week of HTx, the other 21 pts survived until hospital discharge (84%).

Univariate analysis of risk factors for HTx recipients (p<0.05) for poor outcome were: higher creatinine pre- and during ECMO, significant fungal infection at time of HTx, and high exposure to blood products. The following variables did not play a role on survival to hospital discharge: original diagnosis, duration of ECMO support, wait time from listing to HTx, lactate pre and during ECMO, cardiac arrest, indication for ECMO, vascular cannulation site, use of ultrafiltration or bacterial infection.

Conclusion: With the success of pediatric HTx and continuing efforts to decrease waitlist mortality, increasing numbers of children will wait for scarce donor organs. Strategies such as ECMO may be associated with a reasonable short-term survival. Selected pts in whom HTx from ECMO has previously been considered contraindicated (e.g., cardiac arrest leading to ECMO, long time of support, use of ultrafiltration, significant bacterial infections), may have successful outcomes.
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

High-Risk Medical Devices, Children and the F.D.A.: Regulatory Challenges Facing Pediatric Circulatory Support Devices

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Introduction:
Pediatric mechanical circulatory support is a critical unmet need in the United States. Infant- and child-sized ventricular assist devices (VAD) are currently being developed largely through federal contracts through the National Heart, Lung, and Blood Institute (NHLBI). Human testing and marketing of high-risk devices for children raises complex ethical, epidemiologic and regulatory issues that will need to be addressed.

Methods:
Leaders from the U.S. Food and Drug Administration (FDA), NHLBI, academic pediatrics, and industry met in January 2006 for the first FDA Workshop on the Regulatory Process for Pediatric Mechanical Circulatory Support Devices. The purpose was to provide the pediatric community with an overview of the federal regulatory process for high-risk devices and to review the challenges specific to the regulation of pediatric circulatory support devices.

Results:
At present, numerous pediatric circulatory support devices are being developed in the U.S. and abroad. Pediatric circulatory support devices should be eligible for consideration as humanitarian use devices because pediatric circulatory failure is rare and no suitable alternative devices are currently available. The humanitarian device regulatory pathway permits market access without large-scale controlled trial data provided the findings of a smaller trial can support the probable benefit and reasonable safety of the device. Profit cannot be generated for devices approved for humanitarian use. The limited economic incentive for industry is a substantial challenge facing pediatric device development. Other challenges include: (1) limited high-risk device trial experience among pediatric specialists, (2) marked heterogeneity of the patient population, (3) small sample-size on which to formulate regulatory decisions (4) ethical complexity of high-risk testing in children, and (5) potential for significant media interest/scrutiny.

Conclusions:
Pediatric circulatory support offers unprecedented challenges to federal regulators and the pediatric community. Early public discourse, shared appreciation of challenges, and careful clinical trial planning will be critical to avoid unnecessary delays in making potentially life-saving devices available for children. Future collaborative efforts to address these challenges are warranted.
Coagulation Management in Pediatric Mechanical Circulatory Support

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Deutsches Herzzentrum Berlin, Germany

Introduction:
With increased use of ventricular assist devices in children, safe and simple anticoagulation management is required. We investigated 72 patients on mechanical circulatory support with Berlin Heart Excor with a mean age of 7.5 years (range: 2 days – 17 years).

Methods:
The data of 72 children supported by the Berlin Heart Excor system were collected. Between 1992 and October 2000 anticoagulation was managed with heparin by ACT monitoring and without anti-aggregation drugs in 40 children (Group A). Since November 2000 a new anticoagulation regime (anti-aggregation and anti-adhesion drugs depending on platelet aggregation tests, heparin in doses depending on thrombelastography) has been followed in 32 children (Group B). The groups were comparable in terms of demography and disease.

Results:
In group A bleeding complications were seen in 19 patients (47.5 %) and re-exploration of the chest in 14 (35%). Cerebral hemorrhage occurred in 2 patients (5 %). In group B 12 patients presented bleeding complications (38 %) with re-exploration in 8 (25 %) and cerebral hemorrhage in 1 (3 %). Thromboembolic events occurred in group A in 9 patients (23 %) with strokes in 6 (15 %). In Group B 7 patients (22 %) had embolic complications and 2 had strokes (6 %).

In group A the mean time of support was 19 days (range 0-111 days) with a long-term survival of 33 % and in group B the mean time of support was 57 days (range 1-420 days) with a long-term survival of 78 %.

Conclusions:
Embolic and bleeding complications were seen in both groups of patients, but in group B with the present anticoagulation management and triple duration of support the incidence was lower. Since, however, thrombogenicity of the systems continues to be their main problem, further improvement of treatment is required.
Objective:
The purpose of this investigation was to present the first European clinical experience with the new MEDOS DELTASTREAM® DP1 using in a Pulsatile ECMO or VAD options in the pediatric population.

Methods:
Between January 2002 and January 2006, 11 patients required ECMO while 5 patients received an LVAD (Tab. 1) in the San Vincenzo Hospital. Indications were post-cardiotomy heart failure in 14 pts and a fulminant myocarditis in 1 pt. ECMO was established in all pts by cannulation of the RA and aorta. LVAD was instituted by cannulation of the LA and aorta. The DP1, an extracorporeal rotary blood pump, was used as an ECMO and an LVAD device. The pump features a diagonal-flow impeller, and can be used for both continuous and pulsatile modes of perfusion. Priming volume of the pump was approximately 30 ml and it has a flow rate of up to 8 L/min.

Results:
Three deaths occurred in the ECMO group, (1 peritonitis, 1 persistent pulmonary hypertension, 1 major neurologic complication), 1 patient died after LVAD removal for low output syndrome. A 12 year old pt was successfully transplanted on the 8th day of ECMO support and discharged on the 30th day post-HTxt. All other patients were discharged. 3 pumps were changed for pump failure. 1 pump was electively replaced due to improper anticoagulation management. No other thromboembolic adverse events occured. 1 patient required surgical revision for bleeding.

<table>
<thead>
<tr>
<th></th>
<th>ECMO 11 pts</th>
<th>VAD 5 pts</th>
<th>Overall 16 pts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (days)</td>
<td>9 (2 d – 12 yrs)</td>
<td>317 (3 days – 11 yrs)</td>
<td>150 (2 d – 12 yrs)</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>0.3 (0.2 – 1.6)</td>
<td>0.75 (0.2 – 1.8)</td>
<td>0.55 (0.2 – 1.8)</td>
</tr>
<tr>
<td>Support duration (h)</td>
<td>63 (40 – 192)</td>
<td>120 (6 – 600)</td>
<td>72 (36 – 600)</td>
</tr>
<tr>
<td>Weaned</td>
<td>9/11</td>
<td>5/5</td>
<td>11/12</td>
</tr>
<tr>
<td>Discharged</td>
<td>8/9</td>
<td>4/5</td>
<td>9/12</td>
</tr>
<tr>
<td>Mortality (%)</td>
<td>27% (3/11)</td>
<td>20% (1/5)</td>
<td>25% (4/16)</td>
</tr>
</tbody>
</table>

Tab. 1 Results
Median (min, max)
Conclusions:
Our results suggest that the MEDOS DELTASTREAM® DP1 pulsatile pump system can be used as an ECMO or a VAD support. The opportunity to utilize pulsatile flow in post-cardiotomy cardiogenic shock significantly improved the outcomes by producing more physiologic hemodynamics and superior end organ function. Easy implantation and simple management of this device represent the major advantages.
Effects of Pulsatile and Nonpulsatile Perfusion on Vital Organ Recovery in Pediatric Heart Surgery: A Pilot Clinical Study

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**Introduction:** There is controversy concerning the utilization of pulsatile flow during cardiopulmonary bypass (CPB) with regard to improved patient outcomes. The aim of the present study was to evaluate pulsatile perfusion in pediatric patients undergoing CPB in a clinical setting.

**Methods:** Fifty consecutive pediatric patients undergoing open heart surgery for repair of congenital heart disease were prospectively entered into the study and were randomly assigned to either the pulsatile perfusion group (Group P, n = 25) or the nonpulsatile perfusion group (Group NP, n = 25). All patients received identical surgical, perfusional, and postoperative care. Study parameters included intubation time, duration of ICU and hospital stay, the need for inotropic support, pre- and postoperative enzymes (ALT, AST), creatinin, CRP, blood count (leukocytes, hematocrit, platelets), mean urine output (ml/day) and total drainage (ml). Major complications and clinical outcome were documented.

**Results:** There were no statistically significant differences seen in either preoperative or operative parameters between the two groups (age, BSA, weight, X-Clamp and CPB time, base flow, flow rates and hemofiltration).

The Group P, compared to Group NP, had significantly less inotropic support (number of agents 1.48±1.05 vs 2.44±1.03, p = 0.0015; dopamine 6.48±3.27 vs 10.3±4.8 μg/kg/min, p = 0.0023; dobutamine 3.12±6.55 vs 8.03±9.1 μg/kg/min, p = 0.034), less intubation period (20.36±17.02 vs 35.44±30.72 hours, p = 0.038), less duration of ICU (2.16±1.07 vs 4.32±4.21 days, p = 0.028) and hospital stay (7.64±2.48 vs 11.84±6.82 days, p = 0.007).

There were no significant differences in either creatinin,enzyme levels and drainage amounts between two groups. Higher urine output (658.8 ± 210.99 vs 528.2 ± 224.71 ml/day, p = 0.039) during ICU period was observed in Group P.

**Conclusions:** We conclude that the use of pulsatile flow resulted in improved patient outcome in preserving cardiac function and maintaining better renal and pulmonary function (shorter intubation period) in the early post-bypass period.
Seven Years Experiences of Pediatric Cardiopulmonary Bypass: 8,685 cases in Shanghai Children’s Medical Center

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Herein we report our seven-year-experience with 8685 cases cardiopulmonary bypass (CPB) in Shanghai Children’s Medical Center.

Methods and Materials:
Between Apr. 1, 1999, and Dec. 31, 2005, 8685 children with congenital heart disease received CPB in Shanghai Children’s Medical Center. The number of the cases increased every year, from 642 in 1999 (nine months) to 1732 in 2005. The patients younger than 1 year or less than 10kg also increases from 16.5%, 26.0% to 51.4%, 62.4% respectively.

According to the complexity of the operation, different temperature was maintained during the operation, such as normothermia, mild hypothermia, moderate temperature, and deep hypothermia. When deep hypothermia was used, pH stat was adopted by flushing mixed gas of 5% CO\textsubscript{2} and 95% O\textsubscript{2}.

Roller pumps were used for most of the patients, and centrifugal pumps were used in 43 patients. Crystal cardioplegia (St. Thomas II) was used in each patient until blood cardioplegia was introduced in 2003. The formula of the blood cardioplegia was the same as del Nido formula which was used in Children’s Hospital Boston.

Ultrafiltrators were set up for every child less than 10kg, or the patient underwent a second operation. Conventional ultrafiltration (CUF), and modified ultrafiltration (MUF) were used for every patient and balanced ultrafiltration (BUF) was used sometimes.

Results:
The mortalities per year, from 1.81% to 3.70%, are a little higher in the recent two years because the severity of the malformation increased. The most frequent complication is low cardiac output, about 12% in recent years. Arrhythmia, infection, and lung complication were the next three frequent problems postoperatively.

Comments:
CPB is an effective means to support patients during open-heart surgery. With the improvement of the technology, it becomes safer than before. Because the equipment used during bypass are more reliable, normothermia CPB (NCPB) is safe for the simple operation without significant adverse effect on the neurological system. Cardioplegia and ultrafiltration are two important factors. The former should make the heart quiet and keep the cardiac function effective and the latter can concentrate the blood, ameliorate edema and filter some inflammatory mediators out, but it cannot reverse the increase of the inflammatory mediators during bypass.

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Normothermic Bypass in Pediatric Surgery: Technical Aspect and Clinical Experience about 1400 Cases

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Institut Hospitalier Jacques Cartier, Massy, France

Introduction:
Cold cardioplegia is "the standard" in pediatric surgery. Since 2001 we have used normothermic bypass with warm blood cardioplegia in 1400 patients.

Method:
The warming unit is set at 37.5°C to warm the prime and during the whole bypass time. Antegrade cardioplegia is composed of blood drawn from the arterial line to an occlusive pump, and a potassium-enriched solution via an electrical syringe pump. Initial injection is prolonged for one minute after electric cardiac arrest. Reinjections are performed for one minute every 15 minutes. Injection rates are calculated according to the patient body surface area (assuming a physiological coronary flow of 5% of the cardiac output). Efficacy and safety were evaluated from:
- Spontaneous rhythm following aortic unclamping
- Troponin I level
- Clinical outcome

The results were retrospectively compared with those obtained in 950 patients operated on with cold blood cardioplegia.

Results:
Hyperkalemia was not noticed and the water balance was negligible (some milliliters) as blood was reinjected in the bypass circuit. The following parameters differed in a statistically significant fashion (t-test: p<0.05).
- Spontaneous resumption of sinus rhythm after release of aortic clamp: 99% vs 77%
- Troponin I rise < 10 nanograms: 44% vs 37%
- Intensive care length of stay: less than 2 days in 86% of patients vs 75%. This data was mostly due to reduced ventilatory time.

Conclusions:
Although improved clinical outcome may not be due exclusively to "warm heart" surgery, its use was demonstrated to be safe and efficacious. This technique deserves to be considered a valid alternative to "classic" method of myocardial protection in pediatric patients.
Atrial Natriuretic Peptide: Could it be a Marker for Postoperative Recurrent Effusions after Fontan Circulation in Complex Congenital Heart Defects?

Fontan operation and its modifications are procedures that are used for physiological correction of complex congenital heart malformations with a functionally single ventricle.

Atrial natriuretic peptide (ANP) which is a physiological diuretic and vasodilator that - together with the effects of cardiopulmonary bypass - plays an important role in augmenting capillary permeability in Fontan patients. The rise in right atrial pressure and wall stress is an important stimulus for release of ANP. ANP levels were measured pre- and early post-operatively in Fontan group (n=20) and control group (n=20, with simple cardiac defects) to study its influence on and correlation with CVP, mean PAP, PVR, SVR, amount of drainage in early and late postoperative period, ICU duration, and need for colloid supplement. Decreasing the PVR and maintaining efficient urine output are important in management of Fontan circulation. Postoperative ANP values showed negative correlation (r = -0.55) with PVR and negative correlation (r = -0.88) with total drainage. This means that higher the late postoperative ANP level, less the drainage. We conclude that, high levels of ANP measured early during- and late after Fontan operation can be used as markers denoting a successful establishment of Fontan circulation in patients with complex congenital heart defects.
Continuous Cerebral and Myocardial Perfusion During Aortic Arch Repair

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Introduction:
To minimize myocardial ischemia as well as total circulatory arrest, we have repaired aortic arch obstruction with VSD in a one-stage procedure using two different techniques of continuous cerebral and myocardial perfusion.

Methods:
Fifty-seven infants, aged 3-137 days and weighing 1.2-4.2 kg, underwent primary repair of CoA (n=41)/IAA (n=16) with VSD, In 51 patients (37 CoA, 14 IAA), an arterial cannula for CPB was inserted either into the ascending aorta or into the innominate artery. With total CPB, a cross clamp was placed between the innominate and left carotid arteries. An end-to-end arch anastomosis was performed with cerebral perfusion and a non-working beating heart (NWBH). In the remaining 6 patients (4 CoA, 2 IAA), an arterial cannula was placed into the innominate artery. With partial CPB, the innominate artery was snugged proximal to the cannulation site and the ascending aorta was cross-clamped. When both ventricles were adequately kept loaded, the heart ejected to maintain coronary circulation. An extended arch anastomosis was carried out with cerebral perfusion and a working beating heart (WBH).

Results:
Ten patients (5 CoA, 5 IAA) undergoing a NWBH technique required cardioplegic arrest to complete a proximal arch anastomosis, while all 6 patients undergoing a WBH technique had the extended anastomosis without myocardial ischemia. There were 1 hospital death and 1 late death, with an overall survival of 96%.

Conclusions:
End-to-end arch reconstruction is feasible without myocardial ischemia, using the NWBH technique in patients without hypoplastic arch and using the WBH technique in patients with hypoplastic arch.
Novel "Biomechanical" Polymeric Valve Prostheses with Special Design for Aortic and Mitral Position – a Future Option for Pediatric Patients

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**Introduction:**
In children, systemic heart valve replacement with biological prostheses is associated with accelerated valve degeneration; mechanical prostheses require permanent anticoagulation. Furthermore, hemodynamic performance of all available valve substitutes is impaired compared to the natural valve. The pulmonary autograft in aortic position offers excellent hemodynamics and growth potential and but creates a new pathology in the RVOT. Novel "biomechanical" polymeric valve prostheses ("bio"=entirely flexible, "mechanical"=entirely synthetic) with special design for mitral and aortic position have been tested in vitro and in a growing animal model and aim at improved durability without the need for permanent anticoagulation.

**Methods:**
The prostheses are made entirely of polycarbonateurethane (PCU). The trileaflet aortic prosthesis has diminished pressure loss and reduced stress and strain peaks at the commissures. The bileaflet asymmetric mitral valve mimics natural, nonaxial inflow, which creates a left ventricular vortex, saving energy for systole. The valves underwent long-term in-vitro testing and in-vivo testing in a growing calf model (20 weeks; 7 mitral and 7 aortic valves) with comparison to 2 different commercial bioprostheses (7 mitral, 2 aortic).

**Results:**
In-vitro durability of the PCU valves was proved up to 20 years. In-vivo durability and hemodynamics were superior to those of all bioprostheses. Survival of PCU valves versus bioprostheses was 7 versus 2 mitral valves and 5 versus 0 aortic valves, respectively. Two animals with PCU aortic valves died of pannus overgrowth that caused severe left ventricular outflow tract obstruction without changes in the valves. Degeneration and calcification were mild (mitral) and moderate (aortic) in PCU valves but were severe in biological valves. There was no increased thrombogenicity of the PCU valves compared to bioprostheses.

**Conclusion:**
The novel "biomechanical" polymeric valve prostheses were superior to current bioprostheses in growing animal model without the need for permanent anticoagulation and thus, may be a future option for pediatric patients.
Development of a Pneumatically-driven Pump-lung for Rescue Applications

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\textsuperscript{2}Novalung GmbH, Hechingen, Germany

Introduction:
Currently, the main risks of traditional ECMO-therapy are blood loss, high risk of infection and substantial hemolysis. These are particularly due to large blood contact surfaces and shear stress resulting from complex systems. A new system for extracorporeal lung assist is presently being developed at the Helmholtz Institute of Biomedical Engineering in Aachen. A rotating bundle of membrane fibers performs the function of both gas exchange and blood delivery. The pump-lung rotates by means of a gas-driven turbine. The resulting device is transportable and stand-alone and is suitable for rescue applications.

Methods:
The \textit{Highly Integrated Extracorporal Rescue Oxygenation System} (HEROS) is a pneumatically-driven pump-lung. Supplied by an integrated cartridge, gas provides for gas exchange and at the same time generates rotation of an implemented turbine. A hollow cylinder consisting of membrane fibers is powered by the turbine and generates centrifugal forces to deliver blood. Gas exchange is increased by intensive blood mixing between the fibers.

Results:
Preliminary HEROS prototypes provide blood flow of approximately 3 L/min and compensate for internal resistance. Turbine design was optimized with regard to the required power supply. Evaluation of gas transfer is ongoing.

Conclusions:
The gas exchange system and the driving system are multifunctional: the fibers effect gas exchange and blood delivery, while the gas delivery system effects gas exchange and pneumatic drive, resulting in a compact system configuration. The HEROS is independent of any external energy supply due to the integrated gas cartridge. Reduction of blood-conveying components guarantees less blood contact surface, and consequently maximizes biocompatibility. All items considered, the HEROS is a promising system for pediatric lung assist.
Feasibility of Trans-Hepatic Left Atrial Cannulation for Placement of a Pediatric Percutaneous Ventricular Assist Device

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Introduction:
Pediatric ventricular assist device (VAD) use is increasing. The TandemHeart PTVA system® is a percutaneous VAD with promise in adults. Pediatric use is limited by cannula length and diameter. Trans-hepatic left atrial (LA) cannulation offers a shorter distance, larger potential cannulae and easier placement. No data are available on requirements for cannula length, size, or flow characteristics. We evaluate the feasibility of trans-hepatic cannulation based on direct patient measurements and bench-top modeling.

Methods:
200 patients admitted to the University of Michigan Pediatric Cardio-Thoracic ICU were evaluated. Patients over 14 years and dextrocardic patients were excluded. The distance from the skin between the 10th and 11th ribs at the mid-axillary line to the left-heart border was measured on X-ray (LAD). The LA size was measured on echocardiogram from the subcostal coronal projection (LAS). Based on these measurements, prototype cannulae were fabricated. Bench top testing was performed with a pump speed of 8500RPM, fluid viscosity of 4.0cP, and physiologic atrial and arterial pressures. Inlet pressure and deliverable flows were measured with differing cannula combinations.

Results:
173 patients were eligible. LAD was plotted against weight generating a linear regression curve: LAD=12.41+0.28*wt(kg) (r²= 0.787). 146 patients had interpretable echocardiograms. LAS vs. weight generated the curve: LAS=1.53+0.047*wt(kg) (r²=0.472).

8 to 14 Fr venous cannulae were tested with 5 to 10 Fr arterial cannulae (see table). The proposed design delivers the required flow with a maximum negative pressure in the system of -97.5 mmHg, avoiding hemolysis.

<table>
<thead>
<tr>
<th>Weight, Kg</th>
<th>LA Distance, cm ± SD</th>
<th>LA Size, cm ± SD</th>
<th>Estimated Flow needs, LPM</th>
<th>Venous Cannula Size, Fr</th>
<th>Venous Cannula Length, cm</th>
<th>Arterial Cannula Size, Fr</th>
<th>Max. Flow Delivered, LPM</th>
<th>Pump Inlet Pressure, mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3.9</td>
<td>11.7±1 n=41</td>
<td>1.4±0.3 n=40</td>
<td>0.2-0.3</td>
<td>8</td>
<td>17</td>
<td>5</td>
<td>0.301</td>
<td>-75.5</td>
</tr>
<tr>
<td>4-6.9</td>
<td>14.2±1.1 n=50</td>
<td>1.8±0.4 n=40</td>
<td>0.3-0.5</td>
<td>10</td>
<td>19</td>
<td>6</td>
<td>0.643</td>
<td>-71.7</td>
</tr>
<tr>
<td>7-11.9</td>
<td>16.5±1.2 n=31</td>
<td>1.9±0.3 n=23</td>
<td>0.5-0.9</td>
<td>12</td>
<td>24</td>
<td>8</td>
<td>1.148</td>
<td>-83.1</td>
</tr>
<tr>
<td>12-19.9</td>
<td>18.4±1 n=25</td>
<td>2.8±0.8 n=20</td>
<td>0.7-1.2</td>
<td>14</td>
<td>26</td>
<td>8</td>
<td>1.203</td>
<td>-44.3</td>
</tr>
<tr>
<td>20-40</td>
<td>21.1±1.8 n=21</td>
<td>3±0.6 n=18</td>
<td>1-2</td>
<td>14</td>
<td>26</td>
<td>10</td>
<td>2.126</td>
<td>-97.5</td>
</tr>
</tbody>
</table>
Conclusions: Based on this bench-top study, trans-hepatic LA cannulation for percutaneous VAD placement is feasible. The shorter distance and larger vein size allows lower resistance cannula design delivering higher flow rates. Direct measurements, development of functional prototypes, and animal studies to prove safety and efficacy are the next stage in this application.

This study is partially supported by SBIR Grant # 2 R44 HL078077-02 from NHLBI of NIH
IN VIVO Testing of the Levitronix Pediatric VAS

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Purpose
The Levitronix pediatric ventricular assist system (VAS) consists of a polycarbonate centrifugal pump without mechanical bearings or seals with only the impeller having blood interface. The pump utilizes magnetic levitation and is a smaller version of the Levitronix CentriMag VAS designed to be more suited for the pediatric population.

Methods:
The system was evaluated in 8 lambs (20-41 kg) for periods ranging from 24 hours to 30 days. Animals were maintained on heparin and supplemented with aspirin when necessary. In addition to pump hemodynamics, biocompatibility was assessed by laboratory evaluation of hemolysis, platelet activation and hemostatic measures. Necropsy and detailed pump retrieval examination were performed for each animal.

Results:
Study flow targets of 0.5, 1.0, 1.5 and 3.0 liters/minute were achieved. Plasma free hemoglobin averaged ~10 mg/dl. Platelet count, total protein and fibrinogen levels remained stable throughout each run. Flow cytometry and thrombelastogram (TEG) data demonstrated that platelet activation and circulating aggregates increased following VAD implantation but declined after 2 weeks and approached preoperative levels by day 30. No end organ dysfunction was observed. Minor kidney infarcts were present in one animal. All other animals were free of thromboembolism.

Conclusions:
These in vivo studies demonstrate satisfactory pump performance over a range of flows pertinent to the pediatric population. They further demonstrate minimal hemolysis, adequate biocompatibility and preservation of organ function.

Supported in part by R44 HL071376-02 from NIH
Computational Flow and Mass Transfer Analysis of a Pediatric Pump-oxygenator

Brian Fill, BS, a Mark Gartner, ME, a Greg Johnson, PhD, a Marc Horner, PhD, b Jeff Ma, PhD b

a Ension, Inc., Pittsburgh, Pennsylvania, USA, b Fluent, Inc., Lebanon, New Hampshire, USA

Introduction:
Computational fluid dynamics (CFD) techniques are increasingly used to optimize mass transfer performance of blood contacting devices. Ension, Inc., as part of a pediatric circulatory system contract with the National Heart, Lung, and Blood Institute, has developed a custom porous media model and user defined function (UDF) to model the blood flow and mass exchange within a microporous hollow fiber membrane (HFM)-based pump-oxygenator using CFD. This work uses correlations derived from direct fiber simulations to achieve a computationally efficient model of blood flow and mass exchange and has been validated with data from in vitro experiments.

Methods:
A periodic unit volume of the HFM-based rotor was modeled and pressure flow curves were generated over relevant flow rates using Fluent v6 (Fluent, Inc. Lebanon, NH). These data were used to develop an anisotropic porous media model for predicting the flow field within the HFM rotor. The flow data was used in conjunction with a UDF to model oxygen transfer to the blood. Flow and mass exchange simulation data were validated in a mock circulatory loop using bovine blood as the working fluid.

Results:
A three-dimensional model containing 2M cells (hybrid mesh) was constructed and used for prediction of flow and mass exchange. Circulatory loop-based experimental validation was conducted using a custom test apparatus using bovine blood.

Conclusion:
Our computational experiments demonstrate good quantitative agreement with experimentally acquired pressure-flow data. We have obtained qualitative agreement between our computational and experimental results for oxygenation. The success of this work suggests this CFD model can be used as a practical design tool for other similar mass exchange devices.
Computational Fluid Dynamics Evaluation of Steady and Pulsatile Hemodynamic Performance of Pediatric Aortic Cannulae

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Introduction: While the benefits of pulsatile perfusion during cardiac surgery have been heavily debated, there has been only limited work so far on the explication of the detailed flow physics. The objective of the work here is to use time-accurate three-dimensional computational fluid dynamics (CFD) to study the flow in a cannulae-aorta model, and to correlate detailed flow field and integral data, such as energy equivalent pressure (EEP), for both steady and pulsatile flow.

Methods: We follow the standard approach for CFD simulation: geometry definition; grid generation; prescription of initial and boundary conditions and flow conditions; Navier-Stokes flow solution; and post-processing and analysis. Our geometry, as shown in Figures 1 and 2, is an engineering model of an aorta with a DLP® Pediatric Arterial Cannulae. As shown in Figure 3, we are studying 3 different flow waveforms; each with a mean flow rate of $Q_{\text{mean}} = 450$ ml/min. Given the fidelity of our simulation, we directly evaluate EEP and correlate it to the flow field and other fluid dynamics characteristics such as head loss in the cannulae and wall-shear stress in the aorta.

Results and Conclusions: Preliminary simulation results for our CFD model are shown in Figures 1 and 2. The model has approximately 1,500,000 cells and shows sufficient fidelity for resolution of important flow details. Final simulations and analysis are currently being undertaken for completion in late April. It will be shown that CFD is useful for evaluation of hemodynamic performance and design of components for optimum CPB (such as pumps and cannulae), and that important flow physics can be quantified in a rigorous manner.
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

Branka Lukic, Conrad M. Zapanta, Tigran Khalapyan, John Connell, Walter E. Pae, John L. Myers, Ronald P. Wilson, Akif Ündar, Gerson Rosenberg, William J. Weiss
Departments of Surgery and Pediatrics, Penn State College of Medicine, Hershey, PA, USA

Penn State is currently developing a 12ml pulsatile pneumatically driven Pediatric Ventricular Assist Device (PVAD) intended to be used in infants (weight range 5-15 kg). The system consists of a pump housing, seamless blood sac in combination with a diaphragm, mechanical heart valves, and inlet and outlet cannulae. After extensive in vitro testing of the pump in a passive-filling mock circulatory loop, an acute animal study was performed to obtain data with a contracting ventricle. The objectives were to determine the range of pneumatic pressures and time required to completely fill and empty the PVAD under various physiologic conditions, simulate reductions in ventricular contractility and blood volume, and provide data for validation of the mock circulatory loop.

Methods:
The pump was implanted in a 15 kg goat via left thoracotomy with cannulation of the left ventricle and ascending aorta. Two ultrasonic flow probes were placed around the inlet (Qin) and outlet cannulae (Qout), and pressures were measured at the following locations: femoral artery (AP), left atrium (LAP), left ventricle (LVP), pump pneumatic drive line, and pump inlet and outlet cannulae. The pump rate and systolic duration were controlled manually to maintain complete filling and ejection. Systolic and diastolic drive pressures were altered in order to observe the ejection and filling times under different operating conditions.

Results:
Examples are shown in the Table. Exp A: Effect of systolic drive pressure (Psyst) on ejection time. Exp B: Effect of diastolic drive pressure (Pdia) on fill time. Exp C: Pre and post esmolol (500 ml/h, at 1250mg/250ml) effect on ventricular function and pump filling.

Conclusions:
The ejection time increased as the systolic pressure decreased at similar Mean AP. The filling times decreased as diastolic pressure became more negative. Esmolol produced a decrease in left ventricular pressure and required longer pump filling time and reduced LVAD flow.

Acknowledgements
This research is supported by the National Heart, Lung, and Blood Institute (NHLBI) Contract N01-HV-48191.

<table>
<thead>
<tr>
<th>Exp</th>
<th>Psyst (mmHg)</th>
<th>Pdia (mmHg)</th>
<th>Tsyst (ms)</th>
<th>LVP (mmHg)</th>
<th>AP (mmHg)</th>
<th>Qout (l/min)</th>
<th>LVAD rate</th>
<th>Heart rate</th>
<th>Eject (ms)</th>
<th>Fill (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 300</td>
<td>350</td>
<td>15</td>
<td>54</td>
<td>92</td>
<td>1.30</td>
<td>82</td>
<td>88</td>
<td>302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 200</td>
<td>-60</td>
<td>420</td>
<td>15</td>
<td>51</td>
<td>86</td>
<td>1.21</td>
<td>78</td>
<td>382</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B 280</td>
<td>-60</td>
<td>340</td>
<td>10</td>
<td>39</td>
<td>66</td>
<td>1.22</td>
<td>83</td>
<td>103</td>
<td>354</td>
<td></td>
</tr>
<tr>
<td>B 280</td>
<td>0</td>
<td>340</td>
<td>10</td>
<td>44</td>
<td>68</td>
<td>0.84</td>
<td>60</td>
<td>107</td>
<td>490</td>
<td></td>
</tr>
<tr>
<td>C 300</td>
<td>-60</td>
<td>300</td>
<td>11</td>
<td>44</td>
<td>67</td>
<td>1.43</td>
<td>90</td>
<td>102</td>
<td>353</td>
<td></td>
</tr>
<tr>
<td>C 250</td>
<td>-60</td>
<td>300</td>
<td>9</td>
<td>26</td>
<td>41</td>
<td>1.35</td>
<td>85</td>
<td>86</td>
<td>390</td>
<td></td>
</tr>
</tbody>
</table>
Background: The Pennsylvania State University is developing a pulsatile Pediatric Ventricular Assist Device (PVAD) for infants and children. In preparation for implantation studies in animals, we completed an in vivo study in lambs and goats. The objectives of this study were to measure their normal hematologic parameters, and to determine the optimal dosage and monitoring methods for therapeutic anticoagulation prior to the PVAD implantation studies.

Methods: Two healthy lambs and two goats were given varying intravenous doses of heparin, oral warfarin, and oral clopidogrel. Measurements included activated coagulation time (ACT), prothrombin time (PT) and International Normalized Ratio (INR). Thromboelastography (TEG) parameters included R-time, K-time, Angle, and maximum amplitude (MA). Platelet aggregation (PA) was performed on a Chrono-Log Whole-blood lumiaggregometer 560-CA (Chronolog; Havertown, PA, USA) using 10 μM ADP and 1 μg/ml collagen agonists.

Results: For the warfarin study, in the sheep (n = 17), the TEG R and K parameters linearly correlated positively with INR (p < .001) over an INR range of 1 to 7.4, although most data fell in the INR range of 1-2. There was a negative correlation of TEG angle with INR (p < .05). There was no significant correlation of TEG MA with INR. In the goats (n = 6), R and K also correlated positively (p < .003 and .012, respectively), Angle correlated negatively (p < .001), and, in this case, MA correlated negatively (p < .021).

For the clopidogrel study, in sheep (n = 14), there were no significant correlations between TEG and PA (ADP) except in one animal in which K correlated negatively (p < .026) and Angle correlated positively (p < .020) with PA-ADP impedance. There was a tendency for MA to increase with PA (collagen) impedance. In goats (n = 20), there was no significant correlation between TEG parameters and PA-ADP. There was a positive correlation between MA and PA (collagen) impedance (p < .045, both animals pooled), and a weaker negative correlation between both R and K and PA-collagen impedance (p < .074 and p < .112, respectively, both animals pooled).

Conclusions: The effect of warfarin, as measured by the INR, was found to extend the clot reaction time (R) and clot formation (K) times, and slow the rate of clot formation (Angle). Warfarin had no effect on clot strength (MA) in sheep, but a reduction in MA was found in goats with increasing INR. Clopidogrel-induced reductions in PA-ADP were associated with slower clot formation (longer K and reduced Angle) in one lamb. In goats and sheep, clot strength (MA) decreased with PA-collagen impedance, though this effect was stronger in goats.

Acknowledgements
This research is supported by the National Heart, Lung, and Blood Institute (NHLBI) Contract N01-HV-48191.
Extracorporeal Membrane Oxygenation Support for Severe Congenital Trachea Stenosis

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Introduction:
Extracorporeal membrane oxygenation (ECMO) support had been used for cardiopulmonary support in neonate, infants, and adults. Here we report the application of ECMO for severe airway stenosis for which it is impossible to ventilate the patients.

Methods:
Three pediatric patients received emergent ECMO because of hypercarpenea that could not managed by conventional ventilation. The pathology included 1. left pulmonary sling with long segment tracheal stenosis, 2. right lung agenesis with long segment tracheobronchial stenosis, 3 congenital anomaly of bronchial tree. Veno-arterial ECMO was set-up for CO2 retention after induction of anesthesia. The patients then received surgical intervention.

Results:
Before ECMO set-up, the arterial blood gas analysis revealed pH=7.02, 7.08, 7.2 and PCO2=112, 208, 69 mmHg, respectively. After ECMO support, the respiratory acidosis was reversed and the patients could be maintained stable. The operation included 1. sliding tracheoplasty and left pulmonay re-implantation, 2. trachea dilatation and stenting, and 3. resection of the stenotic segment and reconstruction of the bronchial tree. The procedures were performed smoothly. The ECMO duration was 14, 49, 6.4 hours, respectively. All patients successfully weaned-off ECMO.

Conclusions:
The ECMO could provide adequate ventilation support for patient with trachea/bronchial stenosis. Under ECMO support, further reconstructive therapy could be performed with success.
Comparison of the Coronary Artery Blood Flow Between Pulsatile Pump and Non-pulsatile Pump Accompanying Intraaortic Balloon Pump in Extracorporeal Circulation


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**** Emergency medicine, Kunkuk University, Seoul, Korea

Introduction:
In sudden cardiac arrest, the effective maintenance of coronary artery blood flow is an important for myocardial preservation and life saving. The pulsatile blood flow is more physiologic and effective than non-pulsatile flow in extracorporeal cardiac resuscitation. And also, it has been reported that the addition of the intraaortic balloon pump (IABP) to the centrifugal pump (CP) was more effective in restoring hemodynamics than the CP alone. The purpose of the study is to compare the coronary artery blood flow and Energy equivalent pressure (EEP) of pulsatile versus non-pulsatile accompanying IABP in cardiac arrest.

Methods:
Total cardiopulmonary bypass circuit was constructed to six Yorkshire swine, weighing 30-40kg. Animals were randomly assigned to group I (n=7, non-pulsatile CP + IABP) or group II (n=7, pulsatile T-PLS pump). Extracorporeal circulation was maintained for 30minutes in each group with a pump flow of 75ml/kg/min in the same animals, respectively. A 30 cc IABP was placed in the descending aorta in group I.

Results:
The difference of the coronary artery flow was not statistically significant at 10, 20, and 30 minutes after bypass, respectively (27.3 ± 8.38, 24.8 ± 6.73, 28.2 ± 9.79, ml/min in group I vs. 22.7 ± 6.12, 25.0 ± 7.84, 27.7 ± 9.35ml/min in group II; p = NS). Percent changes of mean arterial pressure to EEP were effective in both groups (23.3 ± 6.1 vs. 19.8 ± 6.2 %, p=NS).

Conclusion:
Combining a CP with an IABP generated effective pulsatility and similar amount of coronary flow as TPLS. However, TPLS, pulsatile ECLS may be easier to insert to patient than combining a non-pulsatile ECLS, CP with an IABP for extracorporeal cardiac resuscitation.

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Comparison of Perfusion Modes in Terms of Surplus Hemodynamic Energy Levels in a Simulated Neonatal CPB Model

Akif Ündar, PhD, Branka Lukic, MS, Bingyang Ji, MD, Conrad M. Zapanta, PhD, Allen R. Kunselman, MA, John D. Reibson, BS, William J. Weiss, PhD, Gerson Rosenberg, PhD, John L. Myers, MD

Departments of Pediatrics, Surgery, Bioengineering, and Health Evaluation Sciences, Penn State College of Medicine, Hershey, Pennsylvania, USA

Purpose:
The objective of this investigation was to compare pulsatile vs. non-pulsatile perfusion modes in terms of Surplus Hemodynamic Energy (SHE) levels during cardiopulmonary bypass (CPB) in a simulated neonatal model.

Methods:
The extracorporeal circuit consisted of a Jostra HL-20 heart-lung machine (for both pulsatile and non-pulsatile modes of perfusion), a Capiox Baby RX hollow fiber membrane oxygenator, a Capiox pediatric arterial filter, 5 feet of arterial tubing and 6 feet of venous tubing with a quarter inch diameter. The circuit was primed with the lactated ringers solution. The systemic resistance of a pseudo patient (mean weight 3 kg) was simulated by placing a clamp at the end of the arterial line. The pseudo patient was subjected to five pump flow rates in the 400-800 ml/min range. During pulsatile perfusion, the pump rate was kept constant at 120 bpm. Pressure waveforms were recorded at the pre-oxygenator, post-oxygenator and pre-aortic cannula sites. SHE was calculated using the following formula \( \text{SHE (ergs/cm}^3 = 1,332 \left[ \frac{\int f p dt}{\int f dt} \right] - \text{Mean Arterial Pressure} \) \) (\( f = \text{pump flow and } p = \text{pressure} \)). A total of 60 experiments were performed (n=6 for non-pulsatile and n=6 for pulsatile) at each of the five flow rates. A linear mixed-effects model, which accounts for the correlation among repeated measurements, was fit to the data to assess differences in SHE between flows, pumps, and sites. Tukey’s multiple comparison procedure was used to adjust p-values for post-hoc pairwise comparisons.

Results:
The following table represents the Surplus Hemodynamic Energy results at the pre-aortic cannula stage.

<table>
<thead>
<tr>
<th>Pump Flow Rate (ml/min)</th>
<th>Non-pulsatile Group SHE (ergs/cm³) (Mean ± SD)</th>
<th>Pulsatile Group SHE (ergs/cm³) (Mean ± SD)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1320 ± 91</td>
<td>6324 ± 772</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>500</td>
<td>888 ± 97</td>
<td>5628 ± 1109</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>600</td>
<td>473 ± 111</td>
<td>6730 ± 531</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>700</td>
<td>283 ± 113</td>
<td>6756 ± 1305</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>800</td>
<td>-172 ± 186</td>
<td>9158 ± 933</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

Conclusions:
The Jostra HL-20 roller pump generated significantly higher Surplus Hemodynamic Energy levels in the pulsatile mode when compared to the non-pulsatile mode at all five pump flow rates.
Comparison of Hollow Fiber Membrane Oxygenators with Different Perfusion Modes During Normothermic and Hypothermic CPB in a Simulated Neonatal Model

Akiif Ündar, PhD, Bingyang Ji, MD, Branka Lukic, MS, MD, Conrad M. Zapanta, PhD, Allen R. Kunselman, MA, John D. Reibson, BS, Tigran Khalapyan, MD, William J. Weiss, PhD, Gerson Rosenberg, PhD, John L. Myers, MD

Departments of Pediatrics, Surgery, Bioengineering, and Health Evaluation Sciences, Penn State College of Medicine, Hershey, Pennsylvania, USA

Purpose:
The objectives of this investigation were 1) to compare two hollow fiber membrane oxygenators (Capiox Baby RX vs. Lilliput 1–D901) in terms of pressure drops and Surplus Hemodynamic Energy (SHE) during normothermic and hypothermic cardiopulmonary bypass (CPB) in a simulated neonatal model and 2) to evaluate pulsatile and non-pulsatile perfusion modes for each oxygenator in terms of Surplus Hemodynamic Energy levels.

Methods:
In a simulated patient, CPB was initiated at a constant pump flow rate of 500 ml/min. The circuit was primed with fresh bovine blood. After 5 minutes of normothermic CPB, the patient was cooled down to 25°C for 10 minutes followed by 30 minutes of hypothermic CPB. The patient then underwent 10 minutes of rewarming and 5 minutes of normothermic CPB. At each experimental site (pre- and post-oxygenator and pre-aortic cannula), SHE was calculated using the following formula {SHE (ergs/cm³) = 1,332 [(∫f p dt) / (∫f dt)] – Mean Arterial Pressure} (f = pump flow and p = pressure). A linear mixed-effects model that accounts for the correlation among repeated measurements was fit to the data to assess differences in SHE between oxygenators, pumps, and sites. Tukey’s multiple comparison procedure was used to adjust p-values for post-hoc pairwise comparisons.

Results:
The following table represents the pressure drops of the membranes and pre-aortic cannula SHE results during the hypothermic CPB stage at 25°C.

<table>
<thead>
<tr>
<th>Perfusion Mode</th>
<th>Non-Pulsatile (n=3) (Mean ± SD)</th>
<th>Non-Pulsatile (n=3) (Mean ± SD)</th>
<th>Pulsatile (n=3) (Mean ± SD)</th>
<th>Pulsatile (n=3) (Mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygenator</td>
<td>Capiox</td>
<td>Lilliput</td>
<td>Capiox</td>
<td>Lilliput</td>
</tr>
<tr>
<td>Pressure Drop of the membrane (mmHg)</td>
<td>*21.3 ± 0.5</td>
<td>50.7 ± 0.9</td>
<td>*22 ± 0.0</td>
<td>53.3 ± 0.5</td>
</tr>
<tr>
<td>SHE (ergs/cm³)</td>
<td>1,655 ± 92</td>
<td>1,506 ± 112</td>
<td>&amp; 10,008 ± 1,370</td>
<td>7,531 ± 483</td>
</tr>
</tbody>
</table>

* p < 0.001 Capiox vs. Lilliput within Non-Pulsatile and Pulsatile groups; & p = 0.01 Capiox vs. Lilliput within Pulsatile group.

During normothermic CPB, both oxygenators had patterns similar to those observed under hypothermic conditions.

Conclusions:
The Capiox oxygenator had a significantly lower pressure drop in both pulsatile and non-pulsatile perfusion modes. For each oxygenator, the Surplus Hemodynamic Energy levels were significantly higher in the pulsatile mode.
Closed Chest Cardiopulmonary Bypass to Facilitate Giant Intracranial Aneurysm Clipping in a Pediatric Patient: Future Anesthetic and Neuromonitoring Considerations

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Introduction:
Two adolescents presented with giant anterior circulation intracranial aneurysms for craniotomy and clipping. The neurovascular surgeon believed the sizes and locations of the aneurysms presented technically challenging approaches wrought with significant morbidity without utilizing extracorporeal circulation. Although successful use of this technique has been performed at other institutions in adults, its use in pediatric neurovascular surgery is not as well documented in current literature, mainly as case reports, and was a relatively novel approach at our institution. We will illustrate how changes in anesthetic management and neuromonitoring may improve our care in future cases.

Methods:
A multidisciplinary conference consisting of representatives from neurosurgery, cardiothoracic surgery, anesthesiology, perfusion, and critical care led to a very safe and effective management strategy for the patients. It included closed-chest cardiopulmonary bypass and deep hypothermic circulatory arrest to optimize the operative field and facilitate clipping of the aneurysms. We monitored invasive arterial and central venous pressures.

Pharmacologic neuroprotection was achieved with thiopental infusion.

Results:
When the operative field shared the location with the site of monitors, it became necessary to limit many neuromonitors which we would normally use for DHCA in congenital cardiac lesions. Specifically, the following could not be used: EEG, NIRS, and TEE. Also, the relative overdose of thiopental led to prolonged postoperative sedation; therefore we postulated that the use of propofol could provide similar neuroprotective benefits and yield quicker recovery times for an accurate neurologic assessment.

Discussion:
Pharmacologic neuroprotection might yield faster recovery times if we infused propofol. Also, a unique use of TEE or TTE would be to help in cannulae placement and in separation from bypass.

Conclusions:
We believe that potential morbidity from DHCA outweighed the risks of attempting to clip the giant aneurysms without utilizing closed-chest cardiopulmonary bypass.
Transcranial Doppler Revealed Retrograde Cerebral Artery Flow During Norwood 1 Operation

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**Introduction:** The use of multimodal neuromonitoring for pediatric cardiac patients has been well described; however, it has yet to be established as a standard of care. We present a case of where multimodal neuromonitoring provided indications of compromise that were not suggested by any other standard monitoring modalities.

**Case:** A 6 day (39 week post conceptual age) female born with a hypoplastic left heart syndrome presented for a Norwood stage I palliation. Anesthesia was maintained with Isoflurane and Fentanyl and facilitated with Pancuronium. The patient was haemodynamically stable maintaining a saturation of 87 to 90% with a FiO2 of 21% and a PaCO2 of 55 – 60 mmHg without any inotropic support. Neuromonitoring was achieved using near infrared spectroscopy (NIRS) (Somanetics, INVOS cerebral oximeter), transcranial Doppler (TCD) measurements of the middle cerebral artery (Spencer TCD 100/ Spencer Technologies), and EEG (Cz was used as a common reference (FP1/2 and C3/C4) with a bipolar recording using a longitudinal montage of FP1 to C3, FP2 to C4 and a transverse montage of FP1-FP2 and C3-C4. A 4 channel recording with a paper speed set at 15mm/sec and sensitivity of 70 to 100 uV/cm. Analog EEG signals were recorded between 0.5 and 30Hz). Baseline measurements were established and no unanticipated deviations from baseline were noted. The perioperative time was uneventful, including a period of deep hypothermia and selective cerebral perfusion (SCP), until immediately after weaning from cardio pulmonary bypass when TCD revealed a retrograde flow in the Middle Cerebral Artery (MCA) during diastole. The surgeon was immediately notified. It was hypothesized that the finding was due to retrograde flow caused by diastolic run off to the pulmonary vasculature through the systemic to pulmonary artery shunt which was anastomosed proximally to the innominate artery. The hypothesis was confirmed when (intermittent) clamping of the modified Blalock-Taussig shunt (BTS) resulted in maintenance of ante grade flow in the MCA through out the cardiac cycle. Simultaneous changes were seen in EEG (subtle alpha wave slowing) and in NIRS a decrease of 12% from the baseline value. The BTS was taken down and replaced with a right ventricular to pulmonary artery conduit (Sano). After the procedure TCD revealed antegrade flow in the MCA through out the cardiac cycle. The EEG and NIRS deviations also normalized rapidly. The immediate postoperative phase was uneventful and the child did not show any signs or symptoms of neurologic deficit.

**Discussion:** To our knowledge this is the first report detection of retrograde flow in cerebral arteries by intraoperative TCD monitoring after placement of BTS. The simultaneous changes seen in both the EEG and NIRS during the period of retrograde flow would not have been considered remarkable without significant changes in TCD. The multimodal neuromonitoring, especially TCD, assisted the intraoperative decision making leading to replacement of BTS by a right ventricular to pulmonary artery conduit, which most likely saved the patient from potential neurological complications.
Acute Myocardial Infarction in Young Adult  
A Case Report and Literature Review

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Introduction:  
Acute myocardial infarction (AMI) is the total occlusion of an epicardial coronary artery. It is one of the main causes of mortality in western countries. It is estimated that 2 to 10 % of all AMI's occurs in young patients.

Method:  
The purpose of our case report concerning a 17 year old male who survived AMI is to analyse retrospectively the clinical history, hospital outcome and relationship between thrombophilia and traditional risk factors in young patients with AMI. Our patient was treated surgically, recovered without complication and discharged after 9 days.

Conclusion:  
Early complete revascularization can salvage myocardium and improve survival. To evaluate coronary anatomy and to determine the underlying pathology coronary catheterisation should be performed. Young patients with AMI should be screened for all possible causes of AMI because of the prognosis of the underlying disease. The treatment and management of these patients need further investigations.
Commerrel Diverticulum: Case Report and Surgical Approach to Vascular Rings

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Introduction:
Vascular ring is a vascular compression syndrome that is characterized by dyspnoea, stridor and dysphagia usually shortly after the birth. Emryologically, it results from persistence of some of the symmetrically developing aortic arches, which otherwise should have regressed, and which therefore compress the surrounding structures (trachea/oesophagus). Recurrent respiratory tract infections generally appear earlier, whereas dysphagia occurs later. Vascular rings are complex and have mainly three types and multiple variants; Commerrel diverticulum is a very rare variant.

Material and Method:
Four cases (ages: 6 mo -4 yrs, 3M:1F) of vascular ring were operated in our center. One of these four cases had Commerrel diverticulum (9.5 month, M) and complained of frequently recurring respiratory tract infections accompanied dysphagia. Clinical examination, echocardiography and radiodiagnostic investigations (CXR, MRI and angiographic examination) revealed presence of a vascular ring caused by Commerrel diverticulum, which is a very rare type, and urgent surgery was performed. Surgical approach was performed with left posterior thoracotomy. Subsequent to the careful dissection of the aortic arch and its branches, the ring surrounding the oesophagus and trachea was freed by division of ligamentum arteriosum. In postoperative phase, all of the cases experienced a clinically apparent respiratory relief and a decrease in the frequency of respiratory tract infections. A postoperative angiographic control was performed in this case, and neither residue nor any compression sign was observed.

Conclusion:
Prolonged and recurrently occurring respiratory tract complaints and dysphagia in early infancy and childhood must alert paediatricians about the possibility of the vascular ring being first in line in differential diagnosis. The absence of these symptoms in early infancy does not rule out the possibility of the vascular ring and further investigations should be carried on. Nowadays, new surgical modalities like video-assisted thoracoscopic division are being reported successfully in cases of vascular ring.
Follow-Up of Pediatric Patients with Kawasaki Disease and a Case Report of Kitamura Operation

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Introduction:
Kawasaki disease (KD) also called mucocutaneous lymph node syndrome, is an acute, self limiting small vessel vasculitis with an unknown aetiology, which effects children between 6 months and 5 years. It’s the most common cause of acquired coronary artery disease in childhood leading to coronary artery disease. Major complication of KD is acute myocardial infarct (AMI) and coronary artery aneurysm.

Purpose:
The present study is a retrospective evaluation to analyse the clinical data and management for KD patients as well as the effectiveness of coronary artery bypass grafting (CABG).

Results:
Between 2002 and January 2006 we evaluated preoperative patients characteristics and long term outcome of 18 paediatric patients with a history of KD. Acute disease occurred between 4 months to 14 years of age, Anomalies of the coronary arteries were found in 6 patients ranging in age from 5 months to 10 years. One patient developed AMI, one underwent CABG 5 years after disease onset at an age of 14 years, Kitamura operation is performed successfully.

Conclusion:
Although coronary artery aneurysms and stenosis requiring surgery is rare CABG is the standard therapy when myocardial ischaemia is detected. Kitamura operation provides good growth potential and graft patency.
**Shprintzen (Velo-cardio-facial) Syndrome: A Rare Case**

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**Introduction:**
Shprintzen Syndrome (Velo-cardio-facial; VCFS) is a very rare morbid entity, seen in either familial or sporadic forms, with major clinical findings such as facial dimorphism, cleft palate, cardiovascular—especially conotruncal—anomalies, mild/moderate mental retardation or more commonly observed learning difficulty. Tendency to behavioural disorders and bipolar schizophrenic diseases may be present in these cases. Autosomal dominant inheritance has been reported. VCFS appears as a consequence of microdeletion in the 22q11 chromosomal band. Although each syndrome has different clinical reflections, genetically the defect is located on the same chromosome.

**Case:**
A four year old boy was admitted to our clinic with a syndromic face and the diagnosis of Tetralogy of Fallot. The patient underwent total correction of the cardiac defect. Atypical facial appearance (wide nasal bridge, narrow distance between the eyes, flat cheeks, and long facial features) and cleft palate was present. With the aid of paediatric and genetic consultation (FISH test), Shprintzen Syndrome was confirmed in our case.

One of the conotruncal abnormalities, Tetralogy of Fallot, which represents the cardiac component of the syndrome was also present in our patient, and was repaired by total correction. Both early and late postoperative periods of the patient were uneventful. The patient has closely been consulted by a specialist psychologist during and also after hospitalisation period.

**Discussion:**
Shprintzen syndrome is a morbid entity which can be genetically detected. This genetically well determined syndrome results from the microdeletion at 22q11 chromosome. Through the genetic scanning test called FISH test in paediatric cases with suspected facial features, this makes it possible these and such syndromes to be detected earlier and these children to integrated to the social life earlier not only by early surgical intervention to the cardiac and facial deformations but also by a good neurological and/or neuropsychiatric evaluation.

**Key words:** Shprintzen’s Syndrome, chromosome 22q11 deletion, Velo-cardio-facial Syndrome, Conotruncal Cardiac Anomalies
Aortico-Left Ventricular Tunnel, An Unusual Congenital Anomaly In Adult. A Case Report About New Surgical Technique

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Background:
Aortico-left ventricular tunnel is a rare congenital cardiovascular anomaly. A 45 year old man with unstable angina pectoris was referred to our clinic and diagnosed as Aortico-Left Ventricular tunnel.

Method:
We performed a new surgical technique including closure of orifices of the tunnel by resection aorta at left coronary ostuim, reconstruction of aorta with patch plasty and formation of neo left main branch with V.Saphena Magna patch at non coronary leaflet.

Conclusion:
In this technique possibility of aortic regurgitation due to stretching and distortion of the aortic ring and leaflets by primary suture closure of tunnel is eliminated. Control two –dimensional Doppler echocardiography and Cardiac MRT shows excellent result. Postoperative coronary flow was restored and thus anginal symptoms disappear.
Case report: Symptomatic Lipoma in the Interventricular Septum

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Cardiac lipomas which are benign non-myxomatous neoplasms of the heart rare, and lipomas are among those least often encountered. Due to fact that they normally cause no symptoms, diagnosis is often purely accidental. We report the case of a 24-year-old woman presented with palpitations of recent onset, and was found to have a lipoma attached to the left side of interventricular septum (IVS). Transthoracic and transesophageal echocardiogram were performed at all five pump flow rates. and showed a mass in the left side of IVS. The successful surgical excision of the lipoma described. Intraoperative histological diagnosis showed the tumor was lipoma.

Transthoracic echocardiogram showing echogenic mass involving left side of interventricular septum (arrow)
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

Design and Engineering Aspects of Pediatric Support Devices: An Update

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Over the last two decades, mechanical circulatory support has assumed an expanding role in the care of children with heart failure by providing support to the failing myocardium. The increased use is mainly due to increasingly complex repairs of congenital cardiac anomalies in such patients. Options or the pediatric population include miniaturized intraaortic ballon pumps, extracorporeal membrane oxygenation (ECMO) as well as pulsatile and nonpulsatile ventricular assist devices (VADs). However, these options are still limited because of the limited availability of appropriately sized devices. Having recognized the need, the development of miniaturized devices is underway and clinical applications are being evaluated.

The presentation will summarize the particular design and engineering aspects for pediatric circulatory support systems, depending on their intended application. It will provide an overview over currently available devices in Europe and devices under development at the Helmholtz-Institute in Aachen, Germany. This includes miniaturized pulsatile and nonpulsatile blood pumps for pediatric VAD, ECMO and CPB applications as well as highly integrated intravascular and extracorporeal membrane oxygenators.
Cannula Design for Pediatric VADS

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The design of inlet and outlet cannula for ventricular, arterial, atrial cannulation should not only encompass anatomical constraints but also ensure that fluid dynamic similitude is maintained with the larger and successful adult sized designs. The principal of fluid dynamic similitude is well established and is used in the design of many ocean-going vessels, aircraft, buildings, bridges, piping systems and numerous other applications involving fluid flows it is a valuable adjunct to more complex CFD studies.

There are several dimensionless numbers such as the Weber, Froude, Strouhal, and Reynolds numbers that can be used to describe various diverse flows for internal or external flow fields. Although the flow in pediatric VAD cannule is not steady, the Reynolds number is the most applicable number and a first order approximation of similitude neglecting gravitational forces can be obtained by ensuring that the Reynolds number is as close to that of the adult size device as possible, within other constraints.

The design of pediatric cannula has been compared to the design of small caliber vascular grafts for vessel replacement, but this is not necessarily an appropriate comparison. For the small bore vascular graft the only energy source available to pump blood through the small diameter graft is the native heart. Thus a small vascular graft would be limited in the flow and velocity that could be produced in the graft. This limited velocity results in a Reynolds number significantly smaller than one encountered in larger vascular grafts that have a higher patency rate. In the case of VADs there is some latitude in the energy that is available from the pump energy source to push the blood through a small diameter cannula and thus maintaining similitude. The pressure drop in an 18mm diameter typical outlet cannula for an adult VAD at a mean flow of 5 liters per minute is on the order of 10 to 20 mmHg. The pressure drop in a 6mm diameter pediatric VAD cannula at a mean flow of .75 l/min is on the order of 100 mmHg and the Reynolds number in the pediatric cannula is still approximately one fourth of that in the adult cannula. In the healthy human the Reynolds number in a typical 2 mm diameter vessel is an order of magnitude lower than the Reynolds number in the aorta. Were it not for the vessel intima, thrombosis would occur.

There are other significant considerations in cannula design such as bulk material properties, surface chemistry, and surface topography, as well as the cannula overall shape and length. Cannula tip and or cage designs must avoid regions of low shear or stasis and regions of excessive shear stress that could cause hemolysis. The cannula must be atraumatic to the tissue. It should be flexible and at the same time kink resistant to avoid any obstruction. There is no one single solution to cannula design but careful consideration given to sound design principles will help ensure a successful cannula.
Development and Application of the Levitronix Mag-Lev Technology for Pediatric Circulatory Support

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Purpose:
The CentriMag® VAS has been used to support >300 adult cardiogenic shock patients. The purpose of this project is to design a smaller version of the CentriMag® Pump better suited for pediatric patients.

Methods:
The design effort focused on reducing priming volume, incorporating ¼” cannulae connections, minimizing hemolysis at pediatric flows while maintaining compatibility with existing CentriMag® system hardware. The specified operating conditions were 0.5-3 L/min at 200mmHg. A total of 6 pump housing variations and 14 impeller designs were iteratively evaluated to determine the optimum blade outlet height, inlet and outlet blade angle, recirculation gap above the impeller and volute geometry. Bench-top hydraulic performance, efficiency and hemolysis tests were conducted on the resulting prototype design.

Results:
The final pump design met the required pediatric operating conditions with roughly twice the hydraulic efficiency of the adult CentriMag® pump. Hemolysis was approximately 50% of the industry gold standard at 0.5LPM, and the priming volume was reduced to 14mL. The table below summarizes the attributes of the CentriMag® and Pediatric pumps:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adult Pump</th>
<th>Pediatric Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priming Volume</td>
<td>32mL</td>
<td>14mL</td>
</tr>
<tr>
<td>Operating Speed Range</td>
<td>0 – 5,500 RPM</td>
<td>0 – 5,500 RPM</td>
</tr>
<tr>
<td>Flow Range</td>
<td>0 – 9.9 LPM</td>
<td>0 – 3 LPM</td>
</tr>
<tr>
<td>Cannulae connection size</td>
<td>3/8” barb</td>
<td>1/4” barb</td>
</tr>
<tr>
<td>Impeller configuration</td>
<td>open</td>
<td>closed</td>
</tr>
</tbody>
</table>

Conclusions:
Through the use of iterative design and bench-top testing, we were successful in developing a small pediatric pump with low hemolysis generation and improved hydraulic performance and efficiency for the pediatric application. Compared with currently available technology, the Levitronix pediatric blood pump is innovative due to its small size, low priming volume, excellent hemodynamic and hematologic performance, and the elimination of failure modes due to the seals and bearings common in other centrifugal pumps. These characteristics make the Levitronix pump technology ideally suited for temporary cardiac support of neonatal and pediatric aged patients. (supported in part by R44 HL071376 from NIH).
Development of a Tiny Centrifugal Rotary Blood Pump TinyPump\textsuperscript{TM} for Pediatric Super-Mini CPB, ECMO and Ventricular Assistance

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A tiny centrifugal blood pump TinyPump\textsuperscript{TM} having a super-low priming volume of 5ml has been developed for pediatric cardiopulmonary bypass (CPB), extra-corporeal membrane oxygenation (ECMO) and left heart bypass applications. The TinyPump\textsuperscript{TM} has a 30mm diameter impeller with 6 straight-vanes driven by the magnetic coupling force between the outer driver magnets mounted on the motor shaft and the follower magnets inside the impeller. The impeller rotation is supported by a hydrodynamic needle type bearing at its center. Titanium was used as the male part of the bearing attached to the bottom pump casing, while polyethylene was fitted at the center of the impeller. The gap clearance between the stationary titanium male part and rotating polyethylene part was adjusted to be 0.1mm to minimize mechanical damage to the blood cell elements. The external dimensions of the pump are 49 mm in diameter and 42 mm in height with its weight and displaced volume being 75 ml and 150g, respectively. The inflow and outflow port has 1/4” inner diameter connectors.

The TinyPump\textsuperscript{TM} can provide the maximum flow of 5.0L/min against 100 mmHg head pressure at 3800 rpm when 1/4 inch inflow and outflow cannula are used. For pediatric outflow cannula size of 3.0 mm, pump rotational speed of 3800, and for 2.6 mm cannula size, 4600 rpm were required to provide the pump flow of 1.0 L/min against head pressure of 100 mmHg. The hemolysis study using a fresh porcine blood obtained from a local slaughterhouse resulted in the normalized index of hemolysis (NIH) to be 0.0076 which is equivalent to BPX-50.

Left atrial to ascending aorta bypass experiment in 20Kg piglets demonstrated a stable low flow control to 0.1L/min without causing regurgitation when pediatric outflow cannula of 2.6mm, 3.0mm or 4.0mm size was used. In the cardiopulmonary bypass study in 20Kg piglets by combining the TinyPump\textsuperscript{TM} or BPX-50 with a Terumo Baby RX oxygenator (43 ml priming volume), the TinyPump\textsuperscript{TM} required pump rpm of around 4000, while BPX-50 2000 rpm to provide the pump flow of 1.5 L/min. Although the TinyPump\textsuperscript{TM} required approximately twice the rpm of the BPX-50 to attain the flow of 1.5 L/min, the plasma free hemoglobin after two hours of CPB bypass in piglets remained less than 5.0 mg/dl which was similar to BPX-50. The entire priming volume of the circuit with TinyPump\textsuperscript{TM} including the Terumo oxygenator and circuit was 70 ml in comparison to 120ml of the BPX-50. Because of the features of super-low priming volume of 5ml, stable low flow control to 0.1L/min without regurgitation, excellent anti-hemolytic performance, the TinyPump\textsuperscript{TM} is suitable for cardiopulmonary bypass, ECMO and ventricular assistance in infants and neonates without requiring blood transfusion.
Hollow Fiber Oxygenator for Pediatric Application

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Baylor College of Medicine, Houston, TX

ECMO technologies have been well developed and it is routinely applied clinically with excellent outcomes. Unfortunately, there is no up-to-date pediatric membrane oxygenator available in spite of recent advancements of gas exchange membrane technology. So far, at this time the clinically available ECMO oxygenator has been the coil type oxygenator and not hollow fiber type oxygenator. This coil type membrane oxygenator was introduced by Dr. Ted Kolobow during the 1970s. For more than 30 years this oxygenator has been forefront of ECMO oxygenator.

Why do we not have a good modern oxygenator for pediatric ECMO? The reason is simple; there is not a volume of clinical patients to satisfy the commercial needs. However, it is extremely important to develop a better and more effective hollow fiber membrane oxygenator for ECMO application.

For membrane oxygenator, micro porous hollow fiber polyethylene or polypropylene was used. They are hydrophobic membranes and reasonable plasma leak free operation of up to 6 hours. When it was introduced in 1981, this hollow fiber oxygenator was intra-capillary blood perfusion mode; however, current hollow fiber oxygenators used extra-capillary blood circulation mode. Unfortunately for the operation of longer than 6 hours for ECMO, these micro-porous membranes have to be covered with a thin wall, gas permeable membrane. Mera Exceling by Senko Medical Instrument Mfg. Co., Ltd, Tokyo, Japan has such an oxygenator. Another approach was introduced by Dainippon Ink, Tokyo, Japan by employing asymmetrical membrane of polymethylpentene (Menox). This is basically micro-porous membrane but one side of the membrane is non-porous structure. This small and efficient hollow fiber oxygenator was proved to be thrombus free operation for many months utilizing a special heparin coating.

This authors’ group together with Fuji Systems Inc, Tokyo, Japan has attempted to develop a pediatric ECMO oxygenator utilizing homogeneous hollow fiber silicone rubber tubes.

The hollow fiber has a 50μ membrane thickness and a 200μ inner diameter. This thin silicone rubber hollow fiber was achieved with a hyper-rigid silicone compound developed by Shinetsu Chemical Industry, Tokyo, Japan and Fuji Systems, Inc. In this presentation the current state of development of this hollow fiber oxygenator will be summarized.
The need for pulsatility in long-term mechanical circulatory support, for the treatment of end-stage heart failure (HF), remains controversial. Positive displacement (pulsatile) pumps have been implanted for periods up to six years, without pathophysiologic sequelae, in more than ten thousand HF patients as a bridge to transplant (BTT) or as destination therapy (DT).

A new generation of small continuous-flow rotary pumps, are under evaluation in clinical trials, for intermediate to long-term circulatory support. Some are CE-marked for commercial distribution in Europe. While less complex, silent and considerably smaller than the earlier pulsatile systems, rotary pumps are characterized by a non-physiologic, non-pulsatile or reduced-pulsatile flow.

Short-term studies in the experimental animal, with continuous-flow pumps, have documented a number of pathophysiologic findings. These include changes in hormonal circadian rhythm (cortisol, renin), cellular metabolism, baroreceptor response and aortic wall morphology, increased autonomic nervous activity (sympathetic and parasympathetic) and diminished vital organ and peripheral tissue perfusion and vascular contractility. Similar pathophysiologic changes have been seen clinically during the pulseless perfusion of cardiopulmonary bypass.

More recently, smooth muscle cell hypertrophy of the renal cortex arteries was noted following extended continuous-flow circulatory support in experimental animals, not seen in controls. Clinical observation in axial-flow pump BTT recipients, has demonstrated unremitting GI bleeding from arteriovenous malformations that resolved post-transplantation. Diminished peripheral vascular reactivity has also been reported following continuous-flow support.

The late consequences of these pathophysiologic changes and their dependence on the degree of ‘reduced-pulsatility’ – itself a function of ventricular contractility and flow settings – remain to be determined. They may limit the application of continuous flow.
Use of Pulsatile Flow during ECMO

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Introduction

Conventional non-pulsatile perfusion with a centrifugal pump and a high pressure-drop silicone membrane oxygenator used to be the standard components of the circuit during extracorporeal membrane oxygenation (ECMO) in pediatric patients. Recently, new rotary blood pumps have been introduced along with low pressure-drop hollow-fiber membrane oxygenators for chronic support in pediatric ECMO. With these new devices, it is possible to generate adequate pulsatility during ECMO.

The objective of this presentation is to share our recent experiences with new devices and pulsatile flow in pediatric ECMO patients at the San Vincenzo Hospital.

Pulsatile ECMO at the San Vincenzo Hospital

In 2005, our group reported the first clinical experience with pulsatile ECMO in the pediatric population utilizing a MEDOS delta stream rotary blood pump and a hollow fiber membrane oxygenator (1). The initial experience was based on only three patients. Major findings were considered the reduction in the use of inotropic support, the recovery of lactate levels in the first six hours as well as the hemodynamic stability. To date, nine other patients underwent pulsatile ECMO for postcardiotomy heart failure in our institution. All patients received venoarterial cannulation (right atrium – ascending aorta). According to thromboelastography, intermittent heparin infusion was used during support. In the last six patients, no chest recision for bleeding was necessary. Three patients received continuous infusion of fenoldopam in order to optimize splanchic perfusion during support. In the overall experience, three patients died: one patient during support for peritonitis while two patients expired after weaning due to persistent pulmonary hypertension and low output syndrome, respectively. Hemofiltration for acute renal insufficiency was needed in one case. Another patient experienced isolated convulsion without sequelae. Neither epinephrine nor norepinephrine were used during support, and lactate levels were recovered to normal between the sixth and ninth hour. Five patients received hepatic and renal artery Doppler that demonstrate a clear pulsatile flow waveform. Three pumps were replaced during support, one for incorrect anticoagulation management while the other two pumps were electively replaced due to increased energy consumption. Our experience with these new devices at the San Vincenzo Hospital confirmed that the use of pulsatile ECMO in the pediatric population maintains better physiological status during support particularly during the first 24 – 48 hours. Based on our pilot results, pulsatile ECMO improved the outcome of pediatric patients not only in terms of mortality but also provided a significant reduction in morbidity as well.

Reference

End-stage heart failure in children who are facing imminent death requires particular treatment. When both surgical intervention and medication have failed to provide cardiac support the optimal therapy is cardiac transplantation. As there is often a lack of access to donor hearts to bridge patients to heart transplantation other methods have been developed. In many institutions ECMO was until recently and often still is regarded as the technique of choice for first intervention. However, the application of ECMO has well known limitations although in trained hands patients can be successfully treated beyond a period of four or even six weeks. These limitations led to the application of a ventricular assist device which has significantly less restrictions regarding long-term application and immunological activation.

To this day (April 2006) 51 children (mean age 3.7 years, range 1 week to 14 years) were implanted with the Excor system in North America. 26 patients received monoventricular support and 25 patients were supported by a bi-ventricular system.

The Excor system is an extracorporeal pneumatically driven heart support system with a variety of different pump sizes and cannulae which are selected according to the weight and size of the children. The system can be used as a mono or bi-ventricular support system. The pneumatic driver provides a wide range of adjustable pressure values. If necessary the right and left side can be operated independently.

The majority of children suffered from dilated cardiomyopathy (50%), congenital heart disease (22%) and myocarditis (8%). 10% (5 patients) could be weaned from the device due to improvement of cardiac function. The majority of these children had myocarditis (40%, 2 patients). The cumulative time spent on the device adds up to 5.9 patient years. Out of the 51 patients treated 6 (12%) are still on the device, 31 could be successfully transplanted (30 days survival after HTx, 91%), and 9 (18%) patients died. 5 (55%) of the patients who died were supported by a bi-ventricular device which indicates their disease status at the time of the device placement. The overall survival rate until further interventions was 82%.

Anticoagulation and platelet inhibition differed amongst the participating institutions. After implantation of the system the majority applied unfractionated heparin and one or two platelet inhibitors (aspirin, clopidogrel) as well as dipyridamole if indicated. To avoid the negative effect of unfractionated heparin in response to platelet activation some institutions recently, according to the authors’ recommendation, applied fractionated heparin (LMWH) instead, this seems to have significant advantages compared to the conventional anticoagulation regimen.

Depending on the institutions’ anticoagulation regime, pump changes had to be performed in 14 patients after a mean of 37 days (range, 4 – 166 days). Due to their transparency, deposits inside the pumps can be detected and the device can be replaced. The overall cumulative time of an placed pump without the need of a pump exchange averaged out at 120 days.

The application of an extracorporeal cardiac assist device, which allows long-time support, extubation, normal food intake while allowing a significant improvement of the hemodynamic condition without increasing the inflammatory status of the patient, has the potential to successfully bridge children in end-stage heart failure to heart transplantation. Thus, although the significance of retrospective data is limited, the application of the assist device seems to be superior to the use of ECMO.
Guidelines for the Use of Pulsatile Flow During Cardiopulmonary Bypass Procedures in Neonates and Infants

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Although the controversy over the benefits of pulsatile flow continues, several pediatric heart centers have recently started using pulsatile flow during cardiopulmonary bypass (CPB) procedures in neonates and infants. The objective of this presentation is to share practical guidelines for utilizing pulsatile flow in pediatric cardiac patients.

The following are recommendations for the use of pulsatile perfusion during pediatric open-heart surgery.

**Recommendation #1: Literature review for selecting components of the extracorporeal circuit**

An extensive Medline search must be performed in order to identify extracorporeal circuit components that are capable of generating a sufficient quality of pulsatility.

**Recommendation #2: In vitro and in Vivo evaluations of the pump and membrane oxygenator**

After the components of the extracorporeal circuit including heart-lung machine, membrane oxygenator, and aortic cannula are selected, in vitro and in vivo evaluations with pulsatile and non-pulsatile flow are necessary in order to obtain adequate experience with the new system.

**Recommendation #3: Precise quantification of pressure-flow pulsatile and non-pulsatile waveforms**

During in vitro and in vivo experiments, a precise quantification of waveforms in terms of hemodynamic energy levels (energy equivalent pressure and surplus hemodynamic energy) is necessary for direct comparisons between perfusion modes because the generation of pulsatile flow depends on an energy gradient.

**Recommendation #4: Pilot Clinical trials**

A pilot clinical study must be performed before the routine use of pulsatile flow. During the pilot experiments, pulsatile flow should be used during aortic cross-clamping, and blood trauma with either perfusion modes must be measured. A transcranial Doppler as a safety device is highly recommended during CPB.

**Recommendation #5: Routine use of pulsatile flow in pediatric cardiac patients**

After the successful completion of the previous 4 recommendations, pulsatile flow may be used routinely and it may also be triggered with EKG for continuous usage throughout the entire duration of CPB.

**Reference**

Microfluidic Devices for Continuous Blood Plasma Separation and Analysis During Pediatric Cardiac Surgery

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¹) Department of Bioengineering, 205 Hallowell Building, University Park, Pennsylvania, USA
²) Departments of Pediatrics, Surgery, and Bioengineering, Penn State Children’s Hospital, Penn State College of Medicine, Hershey, Pennsylvania, USA

Introduction:
Several studies have shown that cardiac surgery induces systemic inflammatory responses when CPB is used. Systemic inflammation causes many postoperative complications, including vital organ dysfunction and even death. The ability to clinically intervene or even study the inflammatory response to CPB, is limited by the lack of timely measurements of inflammatory responses. This research designed a microanalytical system for online monitoring of inflammatory responses. It includes a plasma autoseparation device and a novel microimmunoassay (μIA) for continuous measurements.

Methods:
A previously designed blood plasma separation device was successfully connected to a heart lung machine. Fresh Bovine Blood hemodiluted to 32% or 26% Hct was introduced from the heart lung machine by connecting the inlet of the separation device to the arterial port of the membrane oxygenator. A second device for continuous plasma analysis is under development. This device is based upon fluid handling circuits coupled to fluorescent cytometric assays. This device uses a specially designed flow structure to allow the cytometric beads to pass between different flow streams for binding without any mixing or dilution of the individual flow streams.

Results: Previous work showing autoseparation of defibrinated sheeps blood demonstrated that between 15-25% of plasma volume could be continuously separated from blood cells as hematocrit increased between 10-35%. Similar device performance was documented with the autoseparation of bovine plasma with a device coupled to a heart lung machine. Continuous biosensing using a bead assay has been demonstrated by quantifying the binding between avidin coated beads and fluorescently labeled biotin.

Conclusions:
Plasma separation coupled to an extracorporeal circuit has been demonstrated. A device which can handle cytometric beads and quantify inflammation markers has also been designed and tested using a avidin-biotin binding assay. These devices are expected to allow studies of the development of systemic inflammation in real-time during CPB procedures.

Successful blood plasma separation using a device integrated with an extracorporeal circuit

36% Hct defibrinated sheep blood at 10 µl/hr 50 µs shutter 20X magnification

Flow Segregation for bead movement without sample dilution (Left) An avidin coated bead enters a FITC-Biotin solution phase (Right) After binding the avidin-biotin-FITC bound bead leaves the solution for fluorescence quantification
Second International Conference on Pediatric Mechanical Circulatory Support Systems and Pediatric Cardiopulmonary Perfusion

Lessons Learned (But Forgotten?) in the Development of Pediatric Cardiopulmonary Assist Devices
Harvey S. Borovetz, Ph.D.
Bioengineering, Surgery & McGowan Institute of Regenerative Medicine, University of Pittsburgh; Pittsburgh, PA.

Pulmonary:
Beginning with the first ECMO devices developed by Drs. Robert Bartlett, Theodor Kolobow and their colleagues more than 30 years ago, teams of investigators have worked toward development of technologies to support infants and small children with congenital and/or acquired cardiopulmonary defects. The ECMO circuits in current use are characterized by either intraluminal or cross flow-based blood oxygenation and decarbonation using microporous hollow fiber networks for gas exchange. When used for circulatory support, ECMO is limited to only a few weeks of use, owing to the requirement for full anticoagulation with heparin. Another limitation of ECMO microporous membranes is so-called “hollow fiber wetting” in which plasma filtrate fills the fiber pores thereby impeding gas exchange and necessitating replacement of the hollow fiber oxygenator.

Cardiac:
The first pediatric ventricular assist devices (VADs) were pulsatile flow devices developed 15-20 years ago either by industry (ABIOMED) or university teams. In the early 1990s, a consortium consisting of Nimbus, Inc and the University of Pittsburgh began the development of a mini-centrifugal pump as a pediatric VAD. The recently awarded (2004) NHLBI Pediatric Circulatory Support contracts have spurred the development of and clinical interest in pediatric VADs, and a first clinical trial of the NHLBI contract devices is under consideration.

Presentation Overview:
This presentation will expand upon the aforementioned history of cardiopulmonary device development with a focus on lessons learned but perhaps now forgotten. One example involves the application of ultra low temperature isotropic (ULTI) carbon to the blood contacting surfaces of etched microchannels and microporous membrane surfaces. The application of ULTI carbon is associated with a marked reduction in cellular deposition to microchannel surfaces; and at coating thicknesses up to one micron, the ULTI carbon imposes a negligible barrier to gas exchange in the membrane oxygenator setting.

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HIT or MYTH: What is The Real Story Behind Pediatric HIT?

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The use of unfractionated heparin (UFH) has long been implicated in the genesis of heparin induced thrombocytopenia (HIT). In fact, heparin-induced antibodies can be found in as many as 25% to 50% of post-operative adult cardiac surgery patients. HIT can elicit a wide range of immunogenic responses that carries serious morbidity (38% to 81%) and mortality (28%). Because of its ease of availability, monitoring, and reversibility, heparin remains the anticoagulant of choice for both the pediatric and adult population undergoing cardiopulmonary bypass. HIT literature has been well reviewed in the adult population, but much less so amongst pediatrics. It is our belief that HIT is underrecognized in the pediatric population. I will outline our experiences with HIT in neonates and children with congenital heart disease (CHD) that approaches the same rate as reported amongst adults. In addition, I will outline our experience with the off-label use of Argatroban.

Rescue Extracorporeal Membrane Oxygenation (ECMO) is the rapid deployment of ECMO to provide immediate cardiovascular support for patients that suffer cardiac arrest. Myocardial dysfunction and/or respiratory failure may be symptoms of a reversible disease process which culminates in cardiopulmonary collapse. Rapid-Deployment ECMO has been successfully utilized by pediatric cardiac centers in patients following sudden cardiac arrest. Pediatric patients with cardiac disease requiring ECMO for cardiac arrest have survival comparable with patients following heart surgery (postcardiotomy) requiring ECMO (40% survival). The face of Extracorporeal Life Support (ECLS) has changed over the past decade. Advances in medical management of respiratory failure, such as high frequency oscillators and inhaled nitric oxide, have led to a decline in the use of ECMO for the neonatal patient with respiratory failure. Concurrently, the use of ECMO for the cardiac patient has increased; more aggressive management postcardiotomy being the primary indication. In an effort to improve outcomes, Rescue ECMO programs have been developed in tertiary pediatric cardiac centers. A pre-assembled and pre-primed ECMO circuit and trained personal must be available in the Critical Care Unit (CCU) 24 hours a day, 7 days a week. There are now over 5,000 pediatric cardiac patients treated with ECLS and registered with the international ELSO database. ELSO reports a survival rate in postcardiotomy patients of 38%, 58% survival in patients with the diagnostic category of myocarditis and 55% with cardiomyopathy. The majority of the patients in the database are postcardiotomy and the survival is dependent in part on the underlying diagnosis. Several complex ethical issues related to ECMO therapy commonly arise during the care of children. Although ECMO is considered standard therapy in most ICU’s, the indications for use in some patient populations is without high level evidence. ECMO is a complex and expensive technology that can be used to provide temporary support during organ failure. Its value for the mature newborn infant with respiratory disease has been validated through clinical trials. Therefore, ECMO support should be actively considered for neonates with severe but potentially reversible respiratory failure. However, clinical trials of ECMO for cardiac patients are limited and complicated by the diversity of clinical indications, small number of patients with a wide variety of cardiac defects and a large number of uncontrolled clinical variables. Each case requires consideration regarding the decision to use ECMO support and is based on the clinical judgment as to whether the benefits outweigh the risks. ECMO may lead to a positive outcome but may also give families false hope, increase patient suffering, and prolong the dying process. ECMO continues to be a satisfactory means of support for short to intermediate term medical support and for eventual myocardial salvage or as a bridge to transplantation if longer periods of support are required. Ongoing development of pediatric cardiac ECMO programs should be encouraged due largely in part to the successful outcomes of these patients, keeping in mind that most of these patients would have died without this aggressive mode of cardiac life support.
Modified Ultrafiltration (MUF) in Pediatric Cardiopulmonary Bypass

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The partnership between cardiopulmonary bypass and ultrafiltration began in the late 1970’s. The bypass circuit was found to be ideally suited for ultrafiltration as it offers easy access to the blood path and provides either a pump or a positive pressure site to drive blood through the hemoconcentrator. Today, the application of ultrafiltration with cardiopulmonary bypass (CPB) is commonplace.

Modified Ultrafiltration (MUF) was introduced in 1991 by Naik et al. at the Hospital for Sick Children in London as a post-CPB technique that was effective in reducing the rise in total body water and tissue edema that often accompanies pediatric CPB.

In their model, using the CPB circuit, the arterial cannula is left in situ so that blood from the aorta is pumped through the hemoconcentrator and warm hemoconcentrated blood returned to the right atrium (AV-MUF). As volume is removed, volume remaining in the CPB circuit is titrated into the patient to maintain filling pressures, MUF has been widely adopted by pediatric heart centers worldwide.

Since the initial reports, several publications on alternative MUF configurations (VV-MUF, VA-MUF) and on how the technical integration of MUF may be safely accomplished have been published.

Among the reported benefits of MUF following pediatric CPB are the reduction in total body water, improved hemodynamics, a decrease in blood transfusion requirements, attenuation of dilutional coagulopathy, a decrease in myocardial edema, improvement in cerebral metabolic recovery following circulatory arrest, improved ventricular function, and improved pulmonary compliance and respiratory mechanics. Some of these benefits, such as pulmonary improvements, may be transient and short-term. Some of the reported benefits may be due to mediator removal.

This MUF presentation will provide an updated literature review, a review of the current practice patterns, and the technical considerations of this technique.
Quality of life and survival of pediatric patients supported with mechanical circulatory support systems depend on reliability and biocompatibility of these devices. One of the major challenges for developers of heart-assist devices, especially those which are intended for pediatric patients, is the reduction of blood damage which is the leading cause of such complications as: thromboemolism, bleeding, neurologic dysfunctions, multi-organ failure, etc. In spite of numerous experimental and computational studies of the causative factors of blood trauma, the mechanisms of blood cell damage remain uncertain. Principal factors hypothesized to be responsible for mechanically-induced blood trauma in assisted blood circulation are abnormal hydrodynamic conditions such as high shear stresses, turbulence and cavitation, and prolonged cell contact with non-biologic surfaces.

Numerous experimental studies of blood trauma have for the most part investigated lethal blood damage (hemolysis). At the same time, sublethal blood trauma, which may cause alterations of patient blood rheology such as an increase in red blood cell (RBC) aggregation and decrease in RBC deformability, has not been adequately characterized. There is some evidence suggesting that sublethal RBC mechanical damage causes the shortening of RBC life span. The concept of sublethal RBC damage was first introduced by Dr. Pierre Galletti, who noted the development of anemia and a reduction of RBC life span in animals placed on extracorporeal perfusion. Clinical data obtained from adult heart-assist device recipients has demonstrated alteration of patient blood rheology. It was found that patients with an implanted artificial heart had decreased hematocrit and RBC deformability and significantly increased viscosity of blood (compared to the viscosity of donor blood from a healthy volunteer measured at the same hematocrit). The decrease in RBC deformability impedes the passage of RBCs through the capillaries. It has been found that naturally aged RBCs, as they become less deformable, are removed from the circulation by the spleen. Therefore, the RBCs exposed to mechanical stress may also be removed from the circulation because of their lower deformability. It is thus hypothesized that a sublethal trauma be considered analogous the RBC aging process in this regard. According to available clinical data, infants have higher fragility of their RBCs than adults. Therefore, the issues mentioned above, may even be more important for pediatric recipients of circulatory assist devices.

This talk will present the effects of mechanically-induced blood damage on the rheological properties of blood and, conversely how blood rheological properties influence blood trauma. The former will include data on the impairment of RBC deformability by mechanical stress alone and in combination with hypothermia and hemodilution (factors related to cardiopulmonary bypass) or hyperthermia. The latter will include the effects of RBC concentration, plasma protein composition and mammalian source of blood on levels of mechanically-induced hemolysis. Our in vitro experimental studies have generated considerable evidence that sublethal mechanical stress significantly impairs rheological properties of blood, and that this impairment may contribute to anemia and even more dangerous complications such as CVA and organ failure. Monitoring and control of hemorheological parameters both in vitro and in vivo may prevent the serious clinical complications observed in patients with mechanical circulatory support devices.
Blood Rheology and PVAD Performance: In-vitro and Animal Models and the Problem of Human Performance Prediction

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In-vitro testing of Artificial Hearts and VADs has always been a strong part of their development (1). Early work focused on the hemolytic potential of these artificial devices—a major concern being areas of high shear and/or high turbulence. Almost all of these studies chose to use a Newtonian blood analog fluid, with the rationale that the non-Newtonian properties would be less important in the high shear flows of major interest. The classic study by Baldwin et al. (2), however, showed that outside of the valve area, the AH/VAD flow did not pose a high risk for hemolysis. Moreover, the growing need for devices suitable for small adults and children led to programs for small and pediatric AH/VADs. In-vivo studies of these smaller pumps showed that thrombosis inside the body of the pump is a major issue. Recent work by Hochareon et al. (3) and Yamanaka et al. (4) have shown the utility of using in-vitro PIV studies to help predict regions of thrombosis in-vivo, by focusing on regions of very low wall shear rate. The rheology of the fluid is certain to play a major role in the development of the flow in these regions.

In the continuum, blood is a shear thinning, viscoelastic fluid. Both the viscosity and elasticity are strong functions of hematocrit. The large range of hematocrit is typical of pediatric blood (5). We have been successful in developing blood analog solutions, with the proper viscoelastic behavior for any hematocrit. Using these analogs, we have found that the major features of the AH/VAD flow fields are strongly influenced by viscoelasticity.

The usefulness and interpretation of both the in-vitro and in-vivo tested of the (Penn State) pediatric heart is made more difficult by the choice of a goat model for the animal testing. Goat blood has little measurable elasticity or shear thinning, a result of small red cell size and low hematocrit. Ideally, one would use the detailed in-vitro testing, using suitable blood analogs, to search for regions of flow stasis in the device. In-vivo regions of clot formation, normally available from only a few animals, might then be used to determine which of the flow regions are most worrisome. Design modifications would proceed on the basis of these results. Flow induced clotting in a goat model, however, may not be directly related to the in-vitro data or indicative of the PVAD’s human performance, and its usefulness and potential for interpretation is further discussed.

Computational Fluid Dynamics and Experimental Characterization of a Miniature Maglev Ventricular Assist Device (VAD) for Children and Adults

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*Department of Surgery, University of Maryland School of Medicine, Baltimore, MD 21201, USA; †Levitronix LLC, Waltham, MA 02451, USA; ‡Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Introduction: The objective of this study is to characterize the hemodynamic performance of a miniature, low-cost ventricular assist device, suitable for univentricular or biventricular support, for use as a bridge to recovery, transplant or a longer term implantable device. The specific design features a novel magnetically levitated configuration, whose key features allow rapid acceleration and deceleration in response to prescribed motor input power cycles. The major advantages of the current design are its small and relatively simple design, its ability to efficiently regulate pump output over a large range of flow conditions, and its ease of production.

Methods: Combined computational fluid dynamics (CFD) analysis and experimental testing were carried out to characterize and optimize the detailed fluid dynamics and hemolytic performance of the newly developed miniature Maglev ventricular assist device (VAD). Three different impeller prototypes were designed and analyzed by CFD, and two prototypes were constructed and tested in-vitro. In addition, a hemolysis model was applied to investigate the shear stress distribution, evaluate the blood damage level, and provide guidance for design optimization.

Results: A comparison of CFD predictions and experimental results showed good agreements. The optimized impeller increased the overall hydro-dynamic output by ~50% over the initial design. The relatively large gap passages (1.5mm) between outer rotor walls and lower housing cavity walls provide a very good surface washing through a secondary flow path while the shear stresses in the secondary flow paths are reduced, resulting in a low rate of hemolysis (NIH = 0.007) without a decrease of the pump’s hydrodynamic performance.

Conclusions: The detailed simulated flow field indicated a well-streamlined flow structure in the main components of the Miniature Maglev pump. Hemolysis analysis indicated that there was no significant high stress regions found in the flow paths, a very low blood damage level (NIH = 0.005) was achieved as a result of the well-designed flow paths. Both experimental and numerical results showed that the optimized impeller can provide adequate hydraulic output over a wide range of physiological operating conditions, and it is capable of meeting the needs of both pediatric and adult patients with severe heart failure.
Initial Experience with the Development and Numerical Analysis for A Low-Pressure Artificial Right Ventricle for Pediatric Fontan Patients

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²Department of Pediatric Cardiology, University of Colorado Health Sciences Center, Denver, CO
³Cardiothoracic Surgery, Children’s Hospital, Denver, CO

Introduction:
Fontan operation is a palliative surgery for patients with congenital heart disease. However, the absence of the right ventricle predisposes them to deteriorative hemodynamic response. The purpose of the present study was to reverse the downward spiral in pediatric Fontan patients by using a specially designed low-pressure artificial right ventricle (RAV) to lessen venous hypertension while enhancing lung circulation by increasing the pulmonary arterial pressure.

Methods:
The physiology of patients with total cavopulmonary connection (TCPC) was mimicked by 4 cross-linked cylinders, with constant diameter of 10 mm. An offset of 10 mm was used between the inferior and superior vena cava (IVC & SVC) while there was non-offset between left and right pulmonary artery (LPA and RPA). Inside the IVC we simulated a special low-pressure RAV, based on the caval size and the desired pressure increase output (10 ~ 20 mmHg). The final RAV consisted of inducer, impeller, diffuser and casing, measuring 25 mm in length and 9.5 mm in diameter. The rotor was levitated magnetically to minimize hemolysis and thrombosis. The suction effect reduced the venous pressure while the rotor provided pressure energy to boost pulmonary circulation downstream. A transient 3D computational hemodynamics analysis was performed under physiologic conditions.

Results:
The pressures upstream IVC fell below the baseline values, followed by a steady pressure rise downstream the ARV. The pressure rise across the ARV varied between -2.5 and 14.9 mmHg. Most blood particles passed the ARV within 20ms, indicating minimal hemolysis. The portion of IVC return directed to RPA was found to be 25.4%, 36.1% and 49.8% for various offsets of 10mm, 5mm and 0mm between IVC and SVC. Details are presented in the table below.

Conclusions:
By efficiently enhancing lung circulation while lightening venous hypertension, this innovative ARV should alleviate the late attrition in pediatric Fontan patients.
Development of Standard Tests to Examine Viscoelastic Properties of Blood of Experimental Animals for Pediatric Mechanical Support Device Evaluation

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Departments of Surgery and Bioengineering and McGowan Institute of Regenerative Medicine, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

The measurement of plasma free hemoglobin which is released from damaged red blood cells (RBCs) (hemolysis) is a standard practice in the testing of the biocompatibility of mechanical circulatory assist devices including those currently being developed for pediatric use. Results of these in vitro and in vivo tests provide assessment of blood trauma. However, sublethal damage to RBCs, which is not seen in hemolysis testing, can cause changes in RBC mechanical properties such as a reduction in their deformability which may lead to microcirculatory impairment and shortening of cell lifespan. In the present work, we investigated the applicability of measuring viscoelasticity of bovine and ovine whole blood for the evaluation of sublethal damage to RBCs. An increase in blood viscosity and elasticity without changes in hematocrit and plasma viscosity would signify a decrease in RBC deformability. Blood viscoelasticity was assessed using a Vilastic Scientific viscoelastometer with an oscillatory flow generated at a constant frequency (2 Hz) in a capillary tube. Due to the natural absence of RBC aggregation and small RBC size in normal bovine and ovine blood, viscoelastic properties are not well pronounced. However, we found that adjustment of blood hematocrit to a standard level of 40-50% allows for the sensitive assessment of viscoelasticity in these blood types. Blood viscosity and elasticity both demonstrated a pronounced non-Newtonian behavior (Figures 1, 2). Temperature dependence for both viscosity and elasticity was greater than that of water. Both viscosity and elasticity were found to be elevated after blood exposure to a uniform mechanical stress (Figure 3). Thermally rigidified RBCs demonstrated a loss of their viscoelasticity dependence on shear rate. This study demonstrated that the measurements of blood viscoelasticity can be meaningful in bovine and ovine blood. It also suggests that the shear thinning behavior seen in these blood types is mostly due to RBC deformability. Finally, this study showed that tests of

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**Figure 1. Viscosity of bovine blood at various Ht**

<table>
<thead>
<tr>
<th>Ht (%)</th>
<th>Viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>41</td>
<td>14</td>
</tr>
<tr>
<td>51</td>
<td>16</td>
</tr>
</tbody>
</table>

**Figure 2. Ovine blood, Ht=54%**

<table>
<thead>
<tr>
<th>Shear rate (1/sec)</th>
<th>Viscosity (cP)</th>
<th>Elasticity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
<td>10.00</td>
</tr>
<tr>
<td>100</td>
<td>0.10</td>
<td>1.00</td>
</tr>
<tr>
<td>1000</td>
<td>1.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Figure 3. Increase on blood elasticity after exposure to sublethal mechanical stress**

<table>
<thead>
<tr>
<th>Strain</th>
<th>Increase in elasticity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>20</td>
</tr>
<tr>
<td>12.8</td>
<td>30</td>
</tr>
</tbody>
</table>

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Hemodynamic Energy Generated in Combining a Centrifugal Pump with an Intraaortic Balloon Pump

Choon Hak Lim*,‡, Ho Sung Son‡,†, Young Hu Fang‡,*, Jung Joo Lee‡, Bum Soo Kim‡, Chi Bum Ahn‡, Hye Won Lee*‡, and Kyung Sun†,‡
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d† Department of Thoracic and Cardiovascular Surgery, Korea University, Seoul, Korea
‡ Korea Artificial Organ Center, Korea University, Seoul, Korea

Introduction:
It has been reported that the pulsatility created by the addition of the intraaortic balloon pump (IABP) to the centrifugal pump was more effective in restoring hemodynamics than the centrifugal pump (CP) alone. The aim of this study was to examine the pulsatility generated in combining a CP with an IABP in terms of energy equivalent pressure (EEP) and surplus hemodynamic energy (SHE).

Methods:
In each of 5 cardiac arrested pigs, the outflow cannula of the CP was inserted in the ascending aorta, and the inflow cannula of the CP was placed in the right atrium. A 30 cc IABP was subsequently placed in the descending aorta. Extracorporeal circulation was maintained for 30 minutes with a pump flow of 75 ml/kg/min by CP alone or CP with IABP, respectively. Pressure and flow were measured in right internal carotid artery.

Results:
The following results were documented:

<table>
<thead>
<tr>
<th>Group</th>
<th>MAP (mmHg)</th>
<th>Change from MAP to EEP (%)</th>
<th>Pulse pressure (mmHg)</th>
<th>SHE (erg/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>61.8 ± 4.8</td>
<td>0.2 ± 0.3</td>
<td>9.1 ± 1.3</td>
<td>133.2 ± 234.5</td>
</tr>
<tr>
<td>CP + IABP</td>
<td>63.5 ± 1.7</td>
<td>*23.3 ± 6.1</td>
<td>*54.9 ± 6.1</td>
<td>*20219.8 ± 5842.7</td>
</tr>
</tbody>
</table>

MAP, mean carotid artery pressure, *p < 0.01 CP vs CP + IABP

Conclusions:
In cardiac arrested animal model, pulsatility generated in combining a CP with an IABP may be effective in terms of EEP and SHE.
Effect of Continuous and Pulsatile Flow Left Ventricular Assist on Pulsatility in a Pediatric Animal Model of Left Ventricular Dysfunction: Early Results

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Introduction & Methods:
Pediatric ventricular assist devices are being developed that can produce pulsatile flow (PF) or continuous flow (CF). Part of the process of selecting one mode or the other is to understand the consequence of each mode on vascular pulsatility. Differences in vascular pulsatility generated by PF and CF operation of the 3” pediatric cardiopulmonary assist system (pCAS, Ension, Inc.) were investigated while providing left ventricular assistance (LVA) using an infant animal model of left ventricular dysfunction (LVD). Three piglets (11.9 ± 1.3 Kg) acutely underwent implantation of an aortic root flow probe (Transonic Systems) and pressure catheter (Millar Instruments). A 20 Fr. inflow cannula was inserted into the left atrium and a 16 Fr. outflow cannula was inserted into the descending thoracic aorta. The pCAS flow was measured by a clamp-on flow probe (Transonic Systems) on the pump outflow conduit. LVD was created by pharmacologically stabilizing the myocardium followed by sequential coronary artery ligation to achieve reduced systemic pressure (↓ 10 mm Hg) and flow (↓ 33%) with elevated LAP (↑ 5 mm Hg). Instantaneous hemodynamic waveforms were digitally recorded while providing CF or PF (100 and 140 bpm) that was incrementally increased to the maximal flow possible without left atrial collapse. These data were used to calculate vascular input impedance (Zart), energy equivalent pressure (EEP), and surplus hemodynamic energy (SHE) as indices of vascular pulsatility for partial (50% of maximum) and maximum LVA flow.

Results:
CF and PF LVA by the 3” pCAS resulted in favorable hemodynamic rectification while generating equivalent flows. For CF operation, the 3” pCAS generated maximum flows of 1.42 ± 0.42 L/min (flow index 119 ± 33 ml/min/Kg) at 1767 ± 208 RPM. PF operation at 100 bpm generated maximum flows of 1.33 ± 0.28 L/min (flow index 118 ± 13 ml/min/Kg) and at 140 bpm generated maximum flows of 1.37 ± 0.09 L/min (flow index 115 ± 12 ml/min/Kg). The maximum flow rates represented near, but not total bypass of the LV. PF LVA maintained a greater degree of pulsatility compared to CF as evidenced by increasing EEP and lesser drop in SHE with increasing pCAS flow (Table 1). Differences in Zart modulus and phase were indiscernible.

<table>
<thead>
<tr>
<th>VAD flow rate</th>
<th>SHE (erg/cm³)</th>
<th>EEP (mmHg)</th>
<th>SHE (erg/cm³)</th>
<th>EEP (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>18,240±5095</td>
<td>74±5</td>
<td>18,976±9929</td>
<td>78±5</td>
</tr>
<tr>
<td>Partial LVA</td>
<td>10,131±3416</td>
<td>82±13</td>
<td>8855±4487</td>
<td>77±9</td>
</tr>
<tr>
<td>Maximum LVA</td>
<td>6,090±2100</td>
<td>83±10</td>
<td>1842±1243</td>
<td>75±8</td>
</tr>
</tbody>
</table>

Conclusions:
The 3” pCAS is capable of delivering a wide range of flow rates appropriate for infants while operating in both CF and PF modes. These acute results suggest that selection of VAD operating mode and flow rate can produce varying levels of SHE and EEP. This selection of flow mode may have long-term consequences on Zart and end-organ perfusion impacting clinical outcomes in pediatric patients. With these differences being identified in the acute setting, the potential superiority of CF or PF LVA remains to be investigated in chronic implantation experiments. [NHLBI Contract No. HHSN268200449189C]
A Model of “pCO₂ gap” During Hypothermic Cardiopulmonary Bypass

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Introduction:
Perfusion adequacy during cardiopulmonary bypass (CPB) is key to reducing post-operative morbidity. The pCO₂ gap (defined as the difference between blood and tissue pCO₂ levels) has been shown to be a sensitive and specific measure of ischemia resulting from inadequate perfusion in pediatric patients undergoing deep hypothermic cardiac arrest (DHCA). A recent study of pediatric ECMO patients has shown that those with a smaller pCO₂ gap had a significantly better survival rate than did patients with a large pCO₂ gap. Practical use of this information is complicated by difficulty in measuring tissue pCO₂ levels. We hypothesize that the pCO₂ gap between tissues and blood can be quantified indirectly by measuring the carbon dioxide level in the sweep gas of the oxygenator, which has been observed to increase dramatically during re-warming.

Methods:
We have developed a mathematical model based on a lumped parameter (compartment) mass balance. The model allows us to examine relationships between tissue pCO₂, plasma pCO₂, and the rate of CO₂ removal through the extracorporeal oxygenator.

Results:
The model predicts carbon dioxide build up in the tissues during hypothermia followed by equilibration with the blood on re-warming. The amount of CO₂ removed by the oxygenator decreases during hypothermia and increases rapidly to greater than baseline (i.e. pre-hypothermia) values upon re-warming.

Conclusions:
The model appears to qualitatively predict CO₂ removal rates observed during DHCA. Refinement and validation of the model may lead to a tool for predicting tissue pCO₂ levels during and after hypothermic cardiopulmonary bypass.
Mechanical Efficiency of Centrifugal Pumps used in ECMO and Ventricular Assist

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Introduction:
The energy used to rotate a centrifugal pump head will give off energy in the form of heat. The amount of heat given off is proportional to the efficiency of the pump. In this study we compared the heat generation of the Biomedicus BP50 and BP80 and the Jostra Rotaflow in low volume circuits.

Methods and Materials:
For this experiment the Jostra Rotaflow, Biomedicus BP50 and Biomedicus BP80 were tested. A low volume circuit was created for each pump. Using ¼-inch and 3/16-inch tubing, the inlet and outlet of the BioMedicus BP50 were connected to a Sarns Cardioplegia 3 M temperature probe 12100. The total circulating volume was 120mL. The experiment was duplicated at 2000, 3000, and 4000 rpms, for each pump head, with flows of 2.7 lpm, 4.0 lpm.

Results:

<table>
<thead>
<tr>
<th>RPM</th>
<th>BP50 Trial 1</th>
<th>BP50 Trial 2</th>
<th>Rotaflow Trial 1</th>
<th>Rotaflow Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>20</td>
<td>22</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>3000</td>
<td>30</td>
<td>32</td>
<td>34</td>
<td>36</td>
</tr>
<tr>
<td>4000</td>
<td>40</td>
<td>42</td>
<td>44</td>
<td>46</td>
</tr>
</tbody>
</table>

The results of this study showed that both types of centrifugal pumps generated heat with a small circuit. The BP50 and BP80 generated significantly higher amounts of heat than the Rotaflow, reaching maximum temperatures of 80.7°C and 78.6°C. On three of the 4 trials with the Biomedicus pump, the device heated the solution to 78°C or higher and the device had a fatal mechanical failure.

Conclusions:
While both the Medtronic and Jostra centrifugal pumps were capable of generating sufficient heat in the small volume circuit, the Jostra Rotaflow proved to be much more mechanically efficient at transferring energy. Centrifugal pumps are the mainstay of many ECMO and VAD programs in many centers around the world. The comparison of heat transfer may be critical for longevity of circuits and avoid dangerous pump head change outs for many patients.
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