Review Article

Clinical overview of the HVAD: a centrifugal continuous-flow ventricular assist device with magnetic and hydrodynamic bearings including lateral implantation strategies

Anamika Chatterjee, Christina Feldmann, Guenes Dogan, Jasmin S. Hanke, Marcel Ricklefs, Ezin Deniz, Axel Haverich, Jan D. Schmitto

Department of Cardiothoracic, Transplantation and Vascular Surgery, Hannover Medical School, Hannover, Germany

Contributions: (I) Conception and design: A Chatterjee, C Feldmann, JD Schmitto; (II) Administrative support: A Chatterjee; (III) Provision of study materials or patients: None; (IV) Collection and assembly of data: None; (V) Data analysis and interpretation: None; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Jan D. Schmitto, MD, PhD, MBA, FCCP, FRCS (Glasg.). Director of the Mechanical Circulatory Support (MCS) Program, Director of the Program of Active Cardiac Implant Technologies Surgical, Director of the Interdisciplinary Heart Failure Unit, Department of Cardiothoracic, Transplantation and Vascular Surgery, Hannover Medical School Carl-Neuberg-Str. 1, 30625 Hannover, Germany. Email: Schmitto.Jan@mh-hannover.de.

Abstract: Growing worldwide incidences of end-stage heart failure and declining rates of cardiac transplants have given rise to the need for alternative treatment options, based on mechanical circulatory support (MCS) devices such as left ventricular assist devices (LVADs). Technologically advanced LVADs such as the HVAD® (HeartWare®, Medtronic) facilitate safe and efficient treatment of heart failure patients with reduced post-operative complications, which is attributed to their considerably miniaturized size. This also facilitates the development and implementation of novel, minimally-invasive surgical techniques. The HVAD is a centrifugal pump, manufactured by HeartWare Inc., (Framingham, MA, USA) and subsequently by Medtronic Inc., (Minnesota, MN, USA), and has been approved for clinical application after receiving the CE Mark approval in 2008 and the FDA approval in 2012. Current research efforts are focused on further miniaturization alongside optimization of electronic and software controllers as well as implementation of the transcutaneous energy transfer (TET) technology. Salient features of the HVAD pump technology, clinical applications and future optimization strategies have been discussed in this article.

Keywords: Centrifugal pump; left ventricular assist device (LVAD); mechanical circulatory support (MCS); heart failure

Submitted Apr 12, 2018. Accepted for publication Apr 16, 2018.
doi: 10.21037/jtd.2018.04.148
View this article at: http://dx.doi.org/10.21037/jtd.2018.04.148

Introduction

Incidences of end-stage heart failure are steadily growing in Europe and the United States (1). The steady state or even declining rates of cardiac transplants worldwide give rise to the need for alternative therapeutic options. Mechanical circulatory support (MCS) in the form of left ventricular assist device (LVAD) implantation is becoming an increasingly viable option for the treatment of terminal heart failure (2,3). Significant technological advancements over the years have led to an increase in ventricular assist device (VAD)-implantation successes. The HVAD is a centrifugal heart pump, manufactured by HeartWare Inc., (Framingham, MA, USA), and subsequently by Medtronic Inc., (Minnesota, MN, USA) which is a very versatile pump, considerably miniaturized to facilitate minimally invasive surgery and reduce surgical complications (4,5). The HVAD received the CE Mark approval in 2008 and the FDA approval in 2012 (5,6). Furthermore, based on the small pump size a minimally invasive implantation technique of HeartWare's HVAD pump became feasible and was

successfully developed at the Hannover Medical School and modified by other VAD-programs (7-18). This article discusses key features of the HVAD, such as its technology, clinical applications and possible future improvements of the pump design.

Pump technology

The HeartWare Ventricular Assist System or HVAD consists of a centrifugal pump, combined with an inflow cannula, an ascending aortic outflow graft with strain relief, as well as a percutaneous driveline. The HVAD pump is continuous-flow and non-pulsatile, lacking mechanical contact points, which ensures a "wearless" system. The wide-blade impeller of the pump is suspended by magnetic as well as hydrodynamic forces and can generate blood flow rates of up to 10 L/min. The HVAD contains two motors to increase reliability by protecting against single-motor faults. The integrated inflow cannula is placed in the left ventricle and is positioned in the pericardial space. Intra-operative adjustments of the pump are facilitated by an adjustable titanium and polyester-based sewing ring. The 10-mm outflow graft contains a strain relief to prevent kinking, and is anastomosed to the ascending aorta. The external system of the HVAD includes a microprocessor controller unit, a monitor, lithium-ion batteries with chargers as well as, AC or DC power adapters. The controller unit is powered by internal, rechargeable batteries and is connected to the monitor with a data port. Patient information from the controller is displayed on the monitor and can be adjusted when required.

Implantation of the HVAD showed reduced intraoperative and postoperative blood product usage and decreased chest tube output as compared to other LVAD types (7). However, computational fluid dynamics comparison of the HVAD with other continuous blood flow pumps revealed the exposure of larger blood volume to shear stresses above 9 Pa in the HVAD (indicating higher propensity for von Willebrand factor cleavage), comparable platelet activation and hemolysis (19). While blood residence times in the HVAD were higher, clinical observations showed similar von Willebrand factor profiles to other pumps (HeartMate II), suggesting similar general blood trauma tendencies in the tested pumps (20,21). The maximum hemodynamic damage was observed in the gap regions at the volute tongue in the HVAD. Further exploration of the correlation between perioperative changes in vWF profile in CF-LVADs patients with early postoperative bleeding events is therefore necessary. Other comparative studies showed significantly lower lactate dehydrogenase levels and thereby increased hemolysis in HVAD patients as compared to patients implanted with other LVAD types (22).

Furthermore, the HVAD is fitted with a periodic speed modulation feature (Lavare™ cycle) which allows alteration of flow patterns within the left ventricle and better control of blood stasis (23). *In vitro* and clinical studies showed the positive effects this feature on intraventricular flow field, allowing ventricular washout and improved adverse event profiles in patients (ReVOLVE trial) (24).

Clinical experience with the HVAD

The first international clinical trial (CE Mark approval study) of the HVAD system was performed by HeartWare from 2006–2007 (24). The study involved the enrollment of 50 patients across five centers (25,26). The objective of the trial was the evaluation of safety and effectiveness of HVAD implantation as a bridge to transplantation in heart-failure patients. Twenty-one out of the first 23 patients successfully survived for at least 180 days following LVAD transplantation. Based on the data generated from the clinical trial, HeartWare Inc. received CE Mark approval for the HVAD in 2008.

Later, another bridge-to-transplant clinical evaluation as part of the FDA approval of the HVAD was conducted on 140 end-stage heart failure patients, across 30 centers in the US (5). The safety of HVAD implantation was evaluated by monitoring patient survival 180 days after implantation, or until LVAD explantation, cardiac transplantation, recovery or death. Data generated from the trial revealed 94% survival in the enrolled patients (5). The HVAD received FDA approval in April, 2012.

Data from the post-CE mark trial of HVAD implantation between February, 2009 and November, 2012 were evaluated as part of ReVOLVE study and revealed 3, 12, 24 and 36 months success rates of 87%, 85%, 79% and 73% respectively (24).

Miniaturization of LVADs is highly advantageous as it increases the versatility of the device and facilitates less invasive surgical procedures (27,28). Minimally invasive surgical procedures are known to result in smaller surgical incisions, reduced bleeding and shorter hospitalization time (29,30). Due to reduced surgical complications, patient survival rates and quality of life are likely to improve. A minimally invasive approach for HVAD implantation

was first developed at the Hannover Medical School in Hannover, Germany in 2011 (20,21). Modifications of this approach also exist and long-term follow up studies were performed to evaluate the safety of the procedure (7,21-24). The HVAD Implantation through this technique has become an established therapy for end-stage left ventricular failure. Prof. Schmitto's team had earlier developed a successful upper hemi-sternotomy and anterior-lateral thoracotomy-based LVAD implantation technique. It was shown to minimize trauma, reduce bleeding, and avoid right heart failure. Both sternotomy-based and minimally invasive HVAD implantation have proved to be successful for treating left ventricular failure (2,6). The CE mark for thoracotomy-based minimally invasive HVAD implantation approach was achieved in 2016.

Future directions

The HVAD is a centrifugal, continuous-flow VAD containing magnetic, hydrodynamic bearings, with proven clinical effectiveness upon implantation with conservative as well as novel, minimally invasive techniques (5,8,12,13,24). There is however, potential for further miniaturization of the pump, as well as optimization of blood flow and pressure measurements. There is already research ongoing to this end, as well as for prevention of post-operative complications such as early and effective thrombus detection and treatment after HVAD implantation, especially through acoustic spectral analysis (31). Efforts are ongoing for optimization of pump speed control and modulation, by redesigning the underlying software, electronics and controller units. Furthermore, research efforts are focused on accommodating exercise adjustment, patient circadian rhythms, endothelialization as well as wireless transcutaneous energy transfer (TET) (32,33). The TET technology would enable a fully implantable pump system with implantable controllers and batteries, which can be recharged intermittently by transcutaneous inductive coupling and communicated with remotely. This technology is thus expected to reduce patient dependence on external batteries.

A potentially optimized version of the HVAD pump has already been produced by HeartWare, termed MVAD and is currently being tested preclinically (34,35). The MVAD pump is a continuous axial flow pump and similar to the HVAD, it possesses "contactless" impeller suspension technology, supporting a wide range of flow rates. The MVAD is a further miniaturized version of the HVAD and is approximately one-third the size of its predecessor. The small size of the MVAD facilitates ventricular support of smaller patients as well as those patients suffering from right ventricular failure. The MVAD pump implantation may facilitate less invasive surgery in contrast to currently available median sternotomy-based ventricular assist devices. The application of minimally invasive techniques for MVAD as well as HVAD implantations is a promising treatment option for heart failure patients. Such focused improvement of pump design, electronics and controller units of HeartWare pumps alongside implementation of innovative energy transfer techniques such as TET, facilitate minimally invasive surgery and realize the potential of a fully transplantable LVAD system, reducing patient dependence on external charging systems for long time periods. Furthermore, increased awareness of device-related differences in blood loss and blood product usage, along with focus on reduction of shear stresses, may also improve VAD patient outcomes (7,19). This would allow a considerable improvement of post-operative patient wellbeing and quality of life.

Acknowledgements

None.

Footnote

Conflicts of Interest: JD Schmitto and G Dogan are consultants of Medtronic. The other authors have no conflicts of interest to declare.

References

1. Weir RAP, McMurray JJV, Velazquez EJ. Epidemiology of heart failure and left ventricular systolic dysfunction after acute myocardial infarction: prevalence, clinical characteristics, and prognostic importance. Am J Cardiol 2006;97:13F-25F.
2. Schmitto JD, Molitoris U, Haverich A, et al. Implantation of a centrifugal pump as a left ventricular assist device through a novel, minimized approach: Upper hemisternotomy combined with anterolateral thoracotomy. J Thorac Cardiovasc Surg 2012;143:511-3.
3. Dixon JA, Spinale FG. Large animal models of heart failure: a critical link in the translation of basic science to clinical practice. Circ Heart Fail 2009;2:262-71.
4. Feldmann C, Chatterjee A, Haverich A, et al. Left

Ventricular Assist Devices - A State of the Art Review. Adv Exp Med Biol 2018;1067:287-94.
5. Aaronson KD, Slaughter MS, Miller LW, et al. Use of an intrapericardial, continuous-flow, centrifugal pump in patients awaiting heart transplantation. Circulation 2012;125:3191-200.
6. Strueber M, O'Driscoll G, Jansz P, et al. Multicenter evaluation of an intrapericardial left ventricular assist system. J Am Coll Cardiol 2011;57:1375-82.
7. Haglund NA, Davis ME, Tricarico NM, et al. Perioperative blood product use: a comparison between HeartWare and HeartMate II devices. Ann Thorac Surg 2014;98:842-9.
8. Schmitto JD, Zimpfer D, Fiane AE, et al. Long-term support of patients receiving a left ventricular assist device for advanced heart failure: a follow-up analysis of the Registry to Evaluate the HeartWare Left Ventricular Assist System. Eur J Cardiothorac Surg 2016;50:834-8.
9. Hanke JS, Rojas SV, Cvitkovic T, et al. First results of HeartWare left ventricular assist device implantation with tunnelling of the outflow graft through the transverse sinus. Interact Cardiovasc Thorac Surg 2017;25:503-8.
10. Popov AF, Mohite PN, Sabashnikov A, et al. Minimally invasive HeartWare LVAD implantation through single left thoracotomy. J Artif Organs 2015;18:170-2.
11. Popov AF, Hosseini MT, Zych B, et al. HeartWare left ventricular assist device implantation through bilateral anterior thoracotomy. Ann Thorac Surg 2012;93:674-6.
12. Haberl T, Riebandt J, Mahr S, et al. Viennese approach to minimize the invasiveness of ventricular assist device implantation†. Eur J Cardiothorac Surg 2014;46:991-6; discussion 996.
13. Maltais S, Davis ME, Haglund N. Minimally invasive and alternative approaches for long-term LVAD placement: the Vanderbilt strategy. Ann Cardiothorac Surg 2014;3:563-9.
14. Maltais S, Anwer LA, Tchantchaleishvili V, et al. Left Lateral Thoracotomy for Centrifugal Continuous-Flow Left Ventricular Assist Device Placement: An Analysis from the Mechanical Circulatory Support Research Network. ASAIO J 2017. [Epub ahead of print].
15. Schmitto JD, Hanke JS, Rojas SV, et al. First implantation in man of a new magnetically levitated left ventricular assist device (HeartMate III). J Heart Lung Transplant 2015;34:858-60.
16. Rojas SV, Hanke JS, Avsar M, et al. Left Ventricular Assist Device Therapy for Destination Therapy: Is Less Invasive Surgery a Safe Alternative? Rev Esp Cardiol (Engl Ed) 2018;71:13-7.
17. Riebandt J, Haberl T, Mahr S, et al. Off-pump HeartWare ventricular assist device implantation with outflow graft anastomosis to the left subclavian artery. Ann Thorac Surg 2014;97:2214-6.
18. Maltais S, Womack S, Davis ME, et al. Surgical Considerations and Challenges for Bilateral Continuous-Flow Durable Device Implantation. ASAIO J 2016;62:e18-21.
19. Thamsen B, Blümel B, Schaller J, et al. Numerical Analysis of Blood Damage Potential of the HeartMate II and HeartWare HVAD Rotary Blood Pumps. Artif Organs 2015;39:651-9.
20. Feldmann C, Zayat R, Goetzenich A, et al. Perioperative onset of acquired von Willebrand syndrome: Comparison between HVAD, HeartMate II and on-pump coronary bypass surgery. PloS One 2017;12:e0171029.
21. Meyer AL, Malehsa D, Budde U, et al. Acquired von Willebrand syndrome in patients with a centrifugal or axial continuous flow left ventricular assist device. JACC Heart Fail 2014;2:141-5.
22. Birschmann I, Dittrich M, Eller T, et al. Ambient hemolysis and activation of coagulation is different between HeartMate II and HeartWare left ventricular assist devices. J Heart Lung Transplant 2014;33:80-7.
23. Zimpfer D, Strueber M, Aigner P, et al. Evaluation of the HeartWare ventricular assist device Lavare cycle in a particle image velocimetry model and in clinical practice. Eur J Cardiothorac Surg 2016;50:839-48.
24. Strueber M, Larbalestier R, Jansz P, et al. Results of the post-market Registry to Evaluate the HeartWare Left Ventricular Assist System (ReVOLVE). J Heart Lung Transplant 2014;33:486-91.
25. Clinical Trials. HeartWare [Internet]. [cited 2016 Nov 9]. Available online: https://www.heartware.com/clinicians/clinical-trials
26. Wieselthaler GM, O Driscoll G, Jansz P, et al. HVAD Clinical Investigators. Initial clinical experience with a novel left ventricular assist device with a magnetically levitated rotor in a multi-institutional trial. J Heart Lung Transplant 2010;29:1218-25.
27. Tarzia V, Buratto E, Gallo M, et al. Implantation of the HeartWare HVAD: from full sternotomy to less invasive techniques. Ann Cardiothorac Surg 2014;3:535-7.
28. Ricklefs M, Hanke JS, Dogan G, et al. Less Invasive Surgical Approaches for LVAD Implantation -State of the Art. Semin Thorac Cardiovasc Surg 2018;30:1-6.
29. Schmitto JD, Mohr FW, Cohn LH. Minimally invasive aortic valve replacement: how does this perform in high-

risk patients? Curr Opin Cardiol 2011;26:118-22.
30. Schmitto JD, Mokashi SA, Cohn LH. Past, present, and future of minimally invasive mitral valve surgery. J Heart Valve Dis 2011;20:493-8.
31. Feldmann C, Deniz E, Stomps A, et al. Local Pump Thrombus Lysis: First In vitro Results with the VAD Maintenance System. Thorac Cardiovasc Surg 2017;65:S1-S110.
32. Bocan KN, Sejdić E. Adaptive Transcutaneous Power Transfer to Implantable Devices: A State of the Art Review. Sensors (Basel) 2016;16.
33. Schmidt T, Bjarnason-Wehrens B, Mommertz S, et al. Changes in Total Cardiac Output and Oxygen Extraction During Exercise in Patients Supported With an HVAD Left Ventricular Assist Device. Artif Organs 2018. [Epub ahead of print].
34. Cheung A, Chorpenning K, Tamez D, et al. Design Concepts and Preclinical Results of a Miniaturized HeartWare Platform: The MVAD System. Innovations (Phila) 2015;10:151-6.
35. Mesa KJ, Ferreira A, Castillo S, et al. The MVAD pump: motor stator core loss characterization. ASAIO J 2015;61:122-6.

Cite this article as: Chatterjee A, Feldmann C, Dogan G, Hanke JS, Ricklefs M, Deniz E, Haverich A, Schmitto JD. Clinical overview of the HVAD: a centrifugal continuous-flow ventricular assist device with magnetic and hydrodynamic bearings including lateral implantation strategies. J Thorac Dis 2018;10(Suppl 15):S1785-S1789. doi: 10.21037/jtd.2018.04.148

